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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 69-FM-165

June 16, 1969

AN ANALYSIS OF THE PERFORMANCE CAPABILITY AND VEHICLE DYNAMICS OF THE SATURN V LAUNCH VEHICLE FOR TWO-ENGINE-OUT MALFUNCTIONS

Flight Analysis Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
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PROJECT APOLLO

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By Samuel R. Newman
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AN ANALYSIS OF THE PERFORMANCE CAPABILITY AND VEHICLE DYNAMICS OF THE SATURN V LAUNCH VEHICLE FOR TWO-ENGINE-OUT MALFUNCTIONS

By Samuel R. Newman

1.0 SUMMARY

The purpose of this document is to present the results of Saturn V S-IC stage two-engine-out simulations and the effect of these malfunctions on vehicle dynamics and performance capability. The results show that for S-IC two-engine-out malfunctions an automatic abort is not necessarily required for certain combinations of engines-out. This situation is demonstrated through a detailed analysis of the vehicle dynamics for these malfunctions and a summary of the vehicle performance capability. In addition, this document should be helpful in crew training and launch simulations for Apollo 11 (Mission G) and subsequent missions.

2.0 INTRODUCTION

A Saturn V two-engine-out study was performed by the TRW Task A-157.3 personnel to define more explicitly the abort procedures required during the launch phase for two-engine-out malfunctions (ref. 1). The results of the simulations performed in this analysis indicate that two-engine-out malfunctions during the S-IC flight times do not require an automatic abort for certain combinations of engines out, and that loss of two engines during the S-II stage of flight does not require an immediate abort if it does not result in loss of control (attitude rates are not exceeded, etc.).

A summary of the vehicle performance capability and a detailed analysis of the vehicle dynamics for S-IC two-engine-out malfunctions are presented in this document. The performance capability is evaluated according to the ability of the vehicle to perform nominal or contingency orbit insertion, and the vehicle dynamics are evaluated in terms of attitude, attitude rates, Q-Ball (ΔP), angle of attack, dynamic pressure, and structural failures.

3.0 ANALYSIS

This analysis was conducted based on the simulation results of a Saturn V two-engine-out study (ref. 1). The study was performed with the TRW N-stage digital computer program, which includes six-degree-of-freedom (6-D) S-IC stage vehicle dynamics and three-degree-of-freedom (3-D) for the S-II stage and S-IVB stage. Also, the operational trajectory and vehicle data for the AS-503 Apollo 8 mission were used in the analysis. The wind profile used for these simulations was a mean December to March wind condition which is relatively mild when compared to a 95 percent or design wind condition. The simulation cases used for this analysis were as follows: S-IC center and one control engine out (cases 2 and 3), dual opposed engines out (cases 4 and 13), and adjacent engines out (cases 5, 8, and 19). It was assumed for the study that for a center and control engine out or dual opposed engines out that the worst case was engines out simultaneously. For the simulations, it was assumed that there was no S-IC/S-II staging limit if the attitude rates were very low (ref. 1). The attitude rate limits for these simulations were the following: pitch and yaw, 4 deg/sec, and roll, 20 deg/sec. A Q-Ball (ΔP) limit of 3.2 psid was used for the simulations, and the launch escape vehicle (LEV) angle of attack limit that was used was taken from reference 1.

4.0 DISCUSSION OF THE RESULTS

4.1 Vehicle Performance

The particular cases were selected to show that S-IC two-engine-out malfunctions during the S-IC flight times do not require an automatic abort for these particular cases. Note that these cases are not all the cases that were presented in reference 1. The vehicle performance capability is presented in figure 1. In figure 1(a) are presented cases 3, 4, and 5: center engine and one control engine out, two dual opposed control engines out, and two adjacent control engines out, each at 46 seconds. (All times refer to ground elapsed time.) The results show that vehicle loss of control occurred and that the vehicle experienced structural failure for each case. In figure 1(b) are presented cases 2 and 13: control engine number 1 and center engine 5 out at 100 seconds, and dual opposed engines 1 and 3 out at 80 seconds. The results indicate that launch vehicle control is maintained, that the abort rate limits were not exceeded, and that the vehicle achieved orbit for both cases. Simulation of a center and control engine out at 90 seconds also achieved orbit but is not presented in this analysis.

In figure 1(c) are presented cases 8 and 19: adjacent control engines 1 and 4 out simultaneously at 100 seconds, and adjacent control engines 2 and 3 out at 100 and 120 seconds, respectively. The results show that for simultaneous engines out vehicle loss of control occurred and the vehicle experienced structural failure. However, when the engines were out sequentially after 100 seconds, the vehicle maintained control, the abort rate limits were not exceeded, and the vehicle achieved orbit.

To summarize, the results of these simulations are as follows.

1. Loss of center engine and one control engine after approximately 85 seconds would not require an automatic abort.

2. Loss of two opposed control engines after approximately 75 seconds would not require an automatic abort.

3. Simultaneous loss of two adjacent control engines at any time will require an automatic abort.

4. Sequential loss of two adjacent control engines after approximately 100 seconds may not require an abort.

4.2 Vehicle Dynamics

4.2.1 Loss of center engine and one control engine (cases 2 and 3).- Case 3 simulated both engines out simultaneously at 46 seconds, and the results are presented in figure 2. The simulation shows that the pitch attitude rate limit is exceeded at 122 seconds, the Q-Ball (ΔP) limit is exceeded at 115 seconds, and the LEV angle of attack limit is exceeded at 90 seconds. Structural failure occurred at approximately 126 seconds. The yaw attitude rate was not exceeded but did reach a peak value of 1.44 deg/sec. The maximum yaw attitude error was 10° and occurred at the time of structural failure. The roll attitude rate was not exceeded but did reach a value of 1.65 deg/sec at 12[illegible] seconds. The maximum roll attitude error was 16.8° at 100 seconds. Note that the maximum dynamic pressure experienced for this simulation was 385 lb/ft^2.

Case 2 simulated both engines out simultaneously at 100 seconds, and results show that launch vehicle control was maintained and the vehicle achieved orbit. These data are presented in figure 3, and the pitch, yaw, and roll attitude rates are plotted through S-IC/S-II separation.

The pitch attitude rate peaked at 104 seconds to a value of 2.72 deg/sec then went to a value of -1.38 deg/sec at 112 seconds. After approximately 120 seconds, the pitch rate reduced to ±0.4 deg/sec. The lowest negative yaw attitude rate was -2.02 deg/sec at 104 seconds, and the highest positive rate was 1.7 deg/sec at 114 seconds. After 120 seconds, the yaw attitude rate reduced to ±0.4 deg/sec. After 100 seconds the roll attitude oscillated between ±0.6 deg/sec.

4.2.2 <u>Loss of two dual opposed control engines (cases 4 and 13)</u>.- Case 4 simulated both engines out simultaneously at 46 seconds, and the results are presented in figure 4. The simulation shows that the pitch attitude rate limit is violated at 114 seconds, the Q-Ball (ΔP) limit is exceeded at 111 seconds, and the LEV angle of attack limit is violated at 106 seconds. Structural failure occurred at approximately 118 seconds. The yaw attitude rate was not exceeded and varied between plus 0.1 deg/sec and minus 0.5 deg/sec. The yaw attitude error remained very low and peaked at time of structural failure to 3.6°. The roll attitude rate was not exceeded and remained very small until 100 seconds, when it peaked to -7.6 deg/sec. The roll attitude error remained almost zero until 100 seconds, when it peaked to -6.0°. The maximum dynamic pressure experienced for this case was 340 lb/ft^2 at 46 seconds.

Case 13 simulated both engines out simultaneously at 80 seconds. The results presented in figure 5 show that launch vehicle control is maintained and that the vehicle achieved orbit. The pitch, yaw, and roll attitude rates are plotted through S-IC/S-II separation. The pitch attitude rate remained very small and varied between ±0.8 deg/sec. The yaw attitude rate remained essentially zero until 145 seconds; it then peaked to -0.65 deg/sec at 148 seconds, then returned to zero for the rest of the flight time.

The roll attitude remained near zero until after S-IC/S-II separation when the rate peaked to +0.67 deg/sec at 230 seconds.

4.2.3 <u>Loss of two adjacent control engines simultaneously (cases 5 and 8)</u>.- The loss of two adjacent control engines simultaneously, numbers 1 and 4, was simulated for cases 5 and 8 at 46 seconds and 100 seconds, respectively. The case 5 data are presented in figure 6 and show that the pitch attitude rate limit is exceeded at 48 seconds, the Q-Ball (ΔP) limit is exceeded at 52 seconds, and the LEV angle of attack limit is violated at 54 seconds. Structural failure occurred at approximately 58 seconds. The yaw attitude rate limit was not exceeded and reached a maximum of 3.2 deg/sec at the time of structural failure. The yaw attitude error reached a peak value of +3.26° at the time of structural failure. The roll attitude rate was not violated and remained very small until time of structural failure, when it peaked at -8.0 deg/sec. The roll attitude error was also small and peaked at structural failure time to +10°. The maximum dynamic pressure for this case was at the time of engines out (46 sec) and was 345 lb/ft^2.

The case 8 data are presented in figure 7. The data show that the pitch attitude rate limit is exceeded at 102 seconds and the yaw roll attitude rate limits are exceeded at 107 seconds. The Q-Ball (ΔP) limit is exceeded at 106 seconds, and the LEV angle of attack limit was not violated. Structural failure occurs at approximately 108 seconds. The yaw attitude error peaked to -12.5° at time of structural failure. The roll attitude error peaked to +18° at time of engine failure and then peaked to -18° at the time of structural failure.

4.2.4 Loss of two adjacent control engines sequentially after 100 seconds (case 19).- The loss of two adjacent control engines (number 2 at 100 sec and number 3 at 120 sec) was simulated for case 19. These data are presented in figure 8 and show that launch vehicle control was maintained and the abort rate limits were not exceeded. The vehicle achieved orbit, but only time histories through S-IC flight are presented. The pitch attitude rate fluctuates between ±3 deg/sec, while the pitch attitude error peaked to +27.8° at 133 seconds. The yaw attitude rate limit was not exceeded. The maximum values were a -2.2 deg/sec and +1.8 deg/sec at 104 seconds and 114 seconds, respectively. The maximum yaw attitude error was +13.0° at 109 seconds. The roll attitude rate limit was not exceeded. It fluctuated between +1.3 deg/sec and -1.5 deg/sec at 126 seconds and 135 seconds, respectively.

The roll attitude error peaked at a positive 2.3° at 122 seconds, then peaked to -8.2° at 132 seconds, and reversed again to a peak value of 2.5° at 142 seconds. Both the roll attitude and roll attitude rate were reduced to very small values after 150 seconds. The maximum Q-Ball (ΔP) for this case was 2.04 psid at 107 seconds. The LEV angle of attack limit was not exceeded for this case.

4.2.5 S-IC two-engine out V, γ summary.- Cases 2, 3, 4, 5, 8 and 13 are summarized in figure 9 in terms of inertial velocity V_i versus inertial flight-path angle γ_i. Three distinct items are presented in this figure.

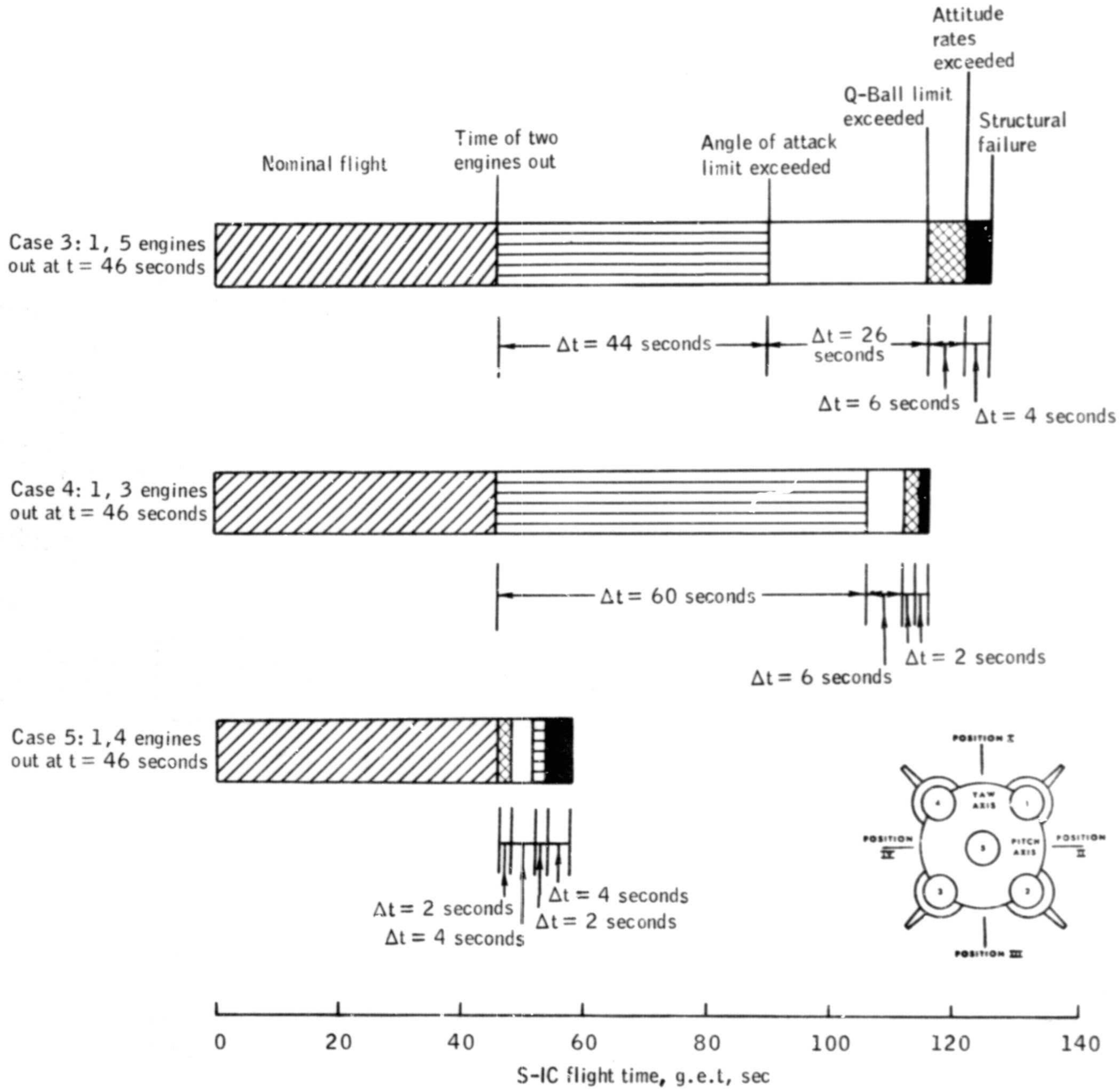
Cases 3, 4, 5 and 8 were two-engine cases at 46 seconds and 100 seconds. Note that these cases deviate from the nominal and exceed the EDS abort limits.

Case 2 is S-IC center engine 5 and control engine 1 out at 100 seconds. Note that this simulation deviates sufficiently from the nominal, does not lose control, and achieves orbit.

Case 13 is S-IC dual opposed control engines 1 and 3 out at 80 seconds. Note that this case penetrates the booster performance envelope (which was not designed for two-engine-out cases); goes to zero flight-path angle; passes through the time of free-fall line (t_{FF}); and achieves orbit.

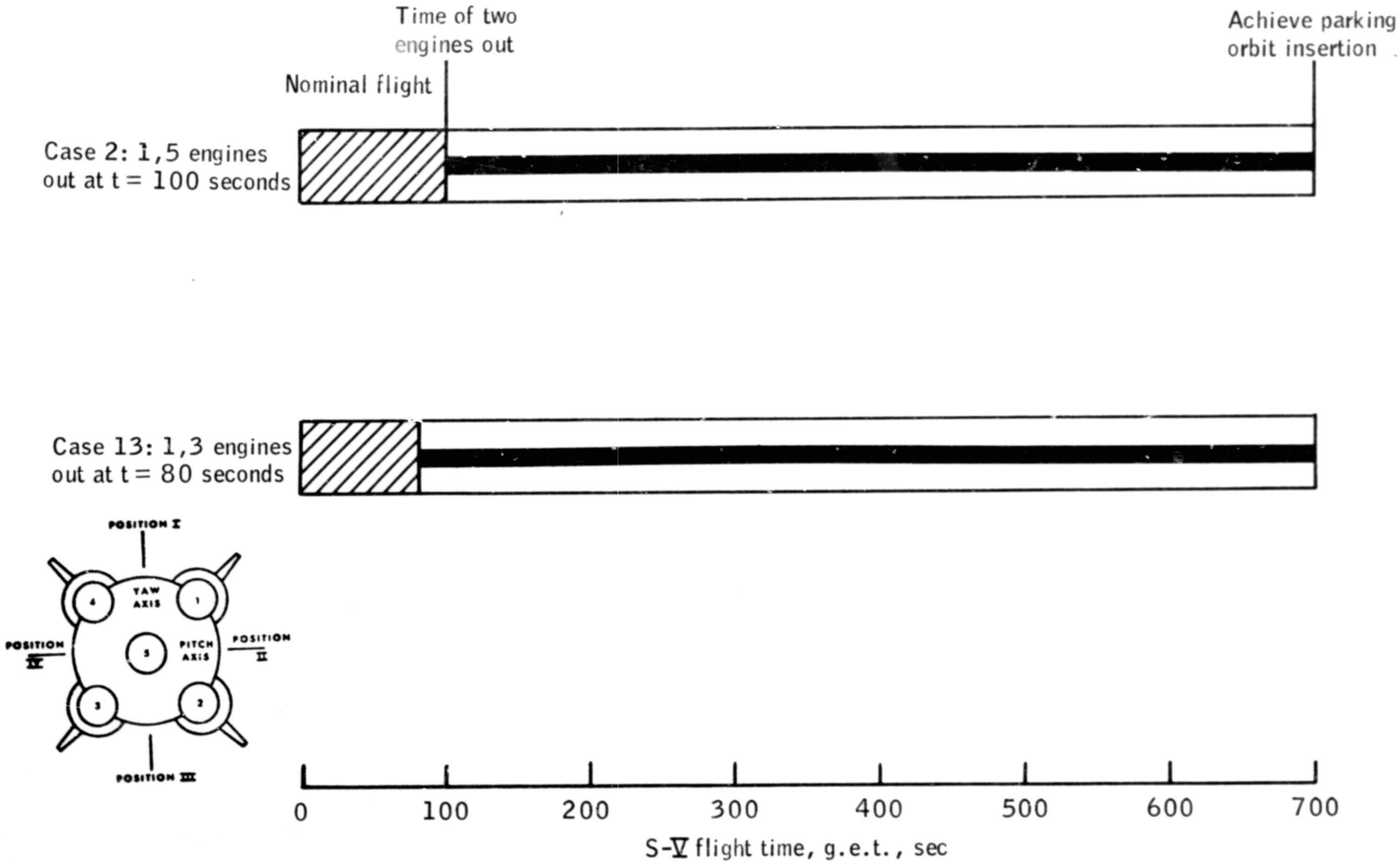
5.0 CONCLUDING REMARKS

The conclusions of this analysis are: two-engine-out malfunctions during the S-IC flight times do not require an automatic abort for certain combinations of engines out after a certain ground elapsed time. This situation is demonstrated through a detailed analysis of the vehicle dynamics for these malfunctions and a summary of the vehicle performance capability. In addition, this document should be helpful in crew training and launch simulations for Apollo 11 (Mission G) and subsequent missions.



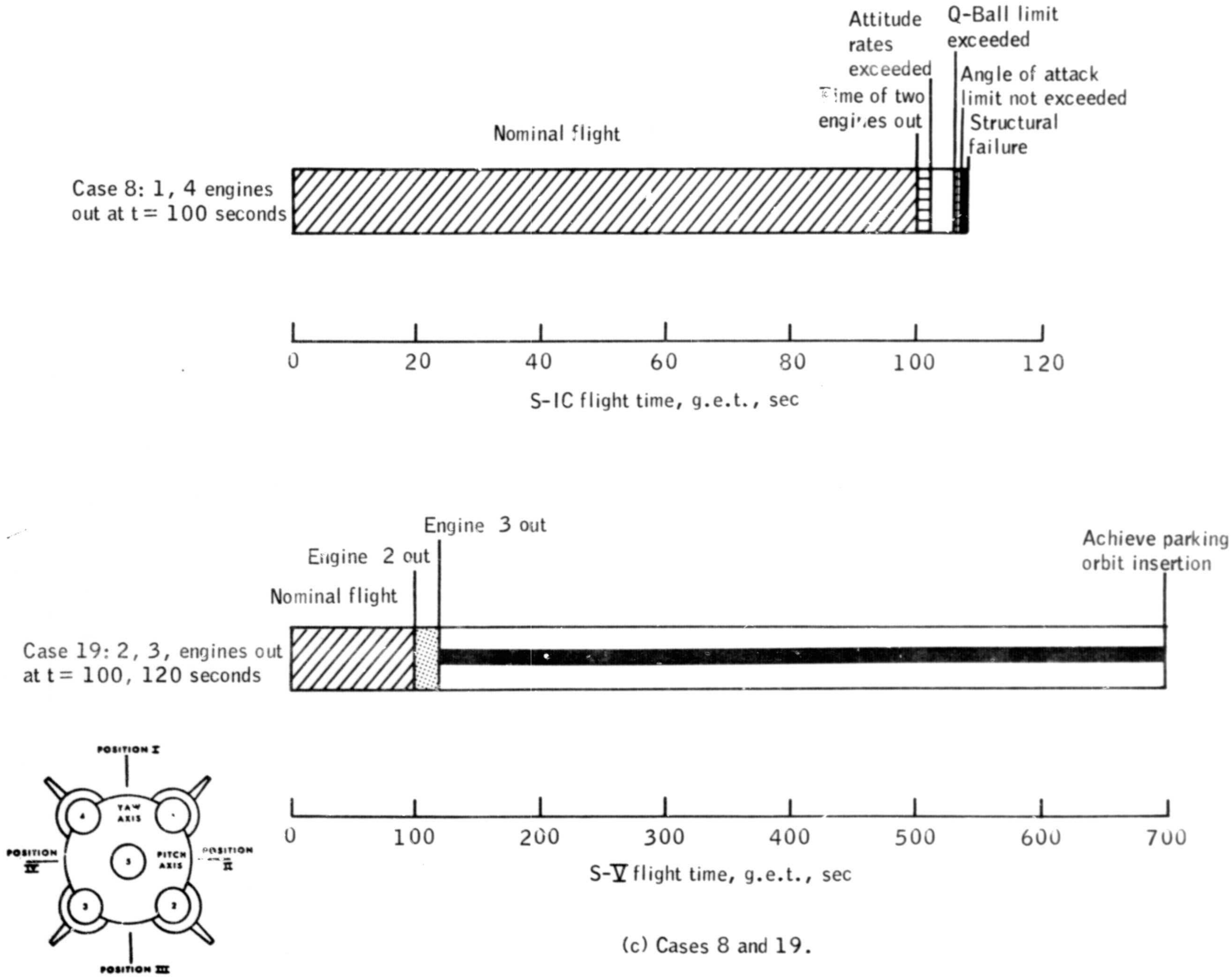
(a) Cases 3,4, and 5.

Figure 1.- Summary of S-IC two-engine-out cases.



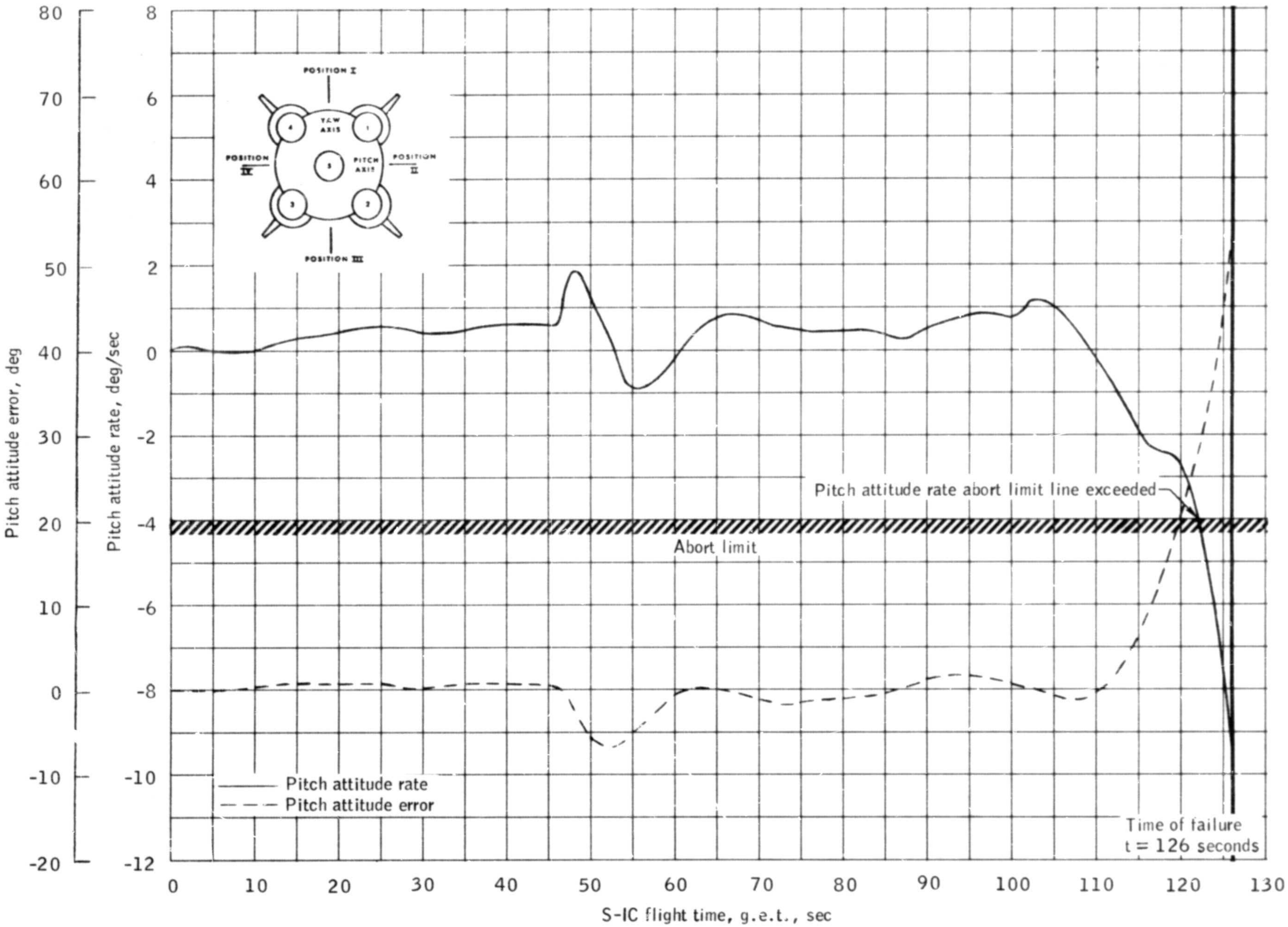
(b) Cases 2 and 13.

Figure 1.- Continued.



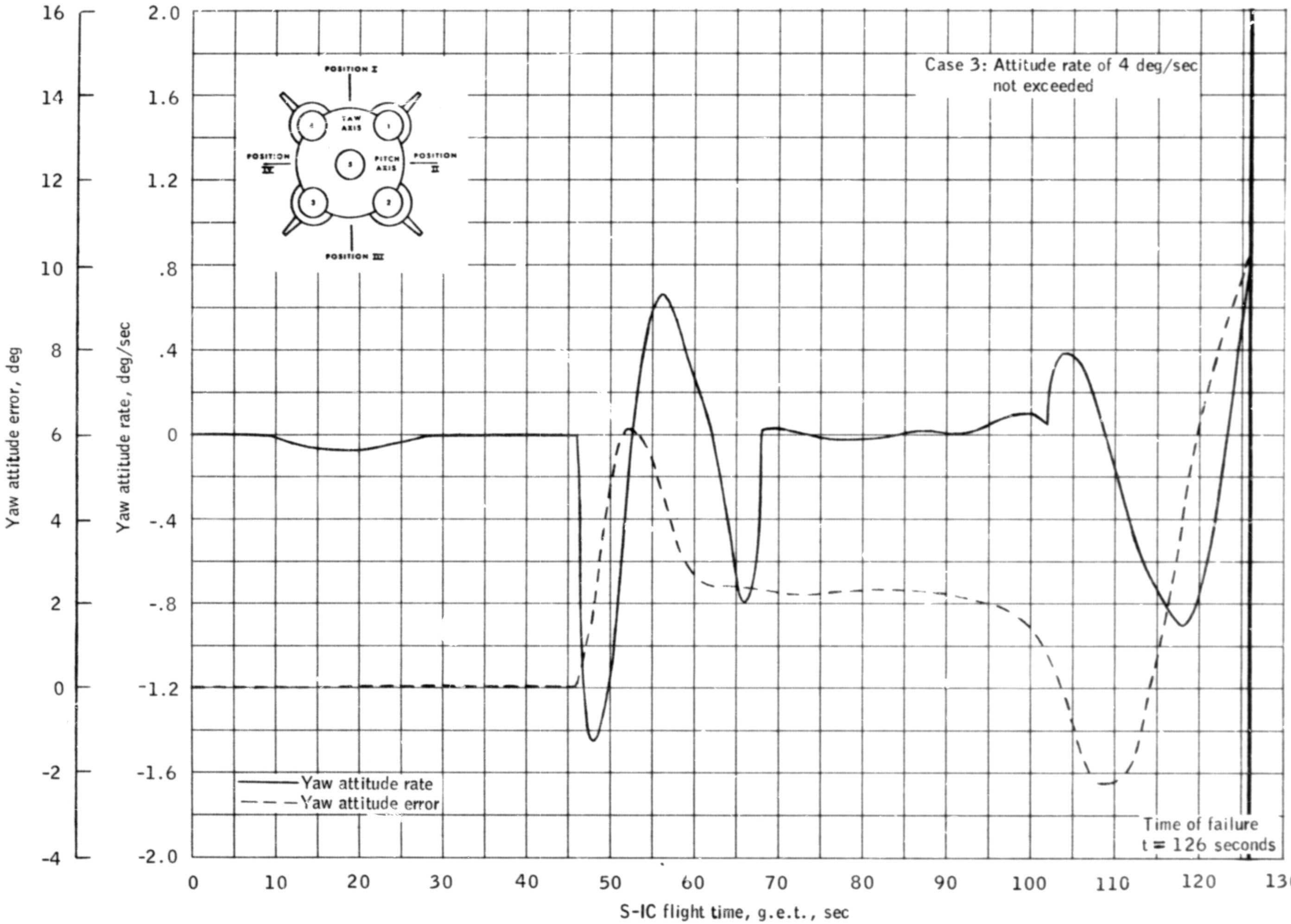
(c) Cases 8 and 19.

Figure 1.- Concluded.



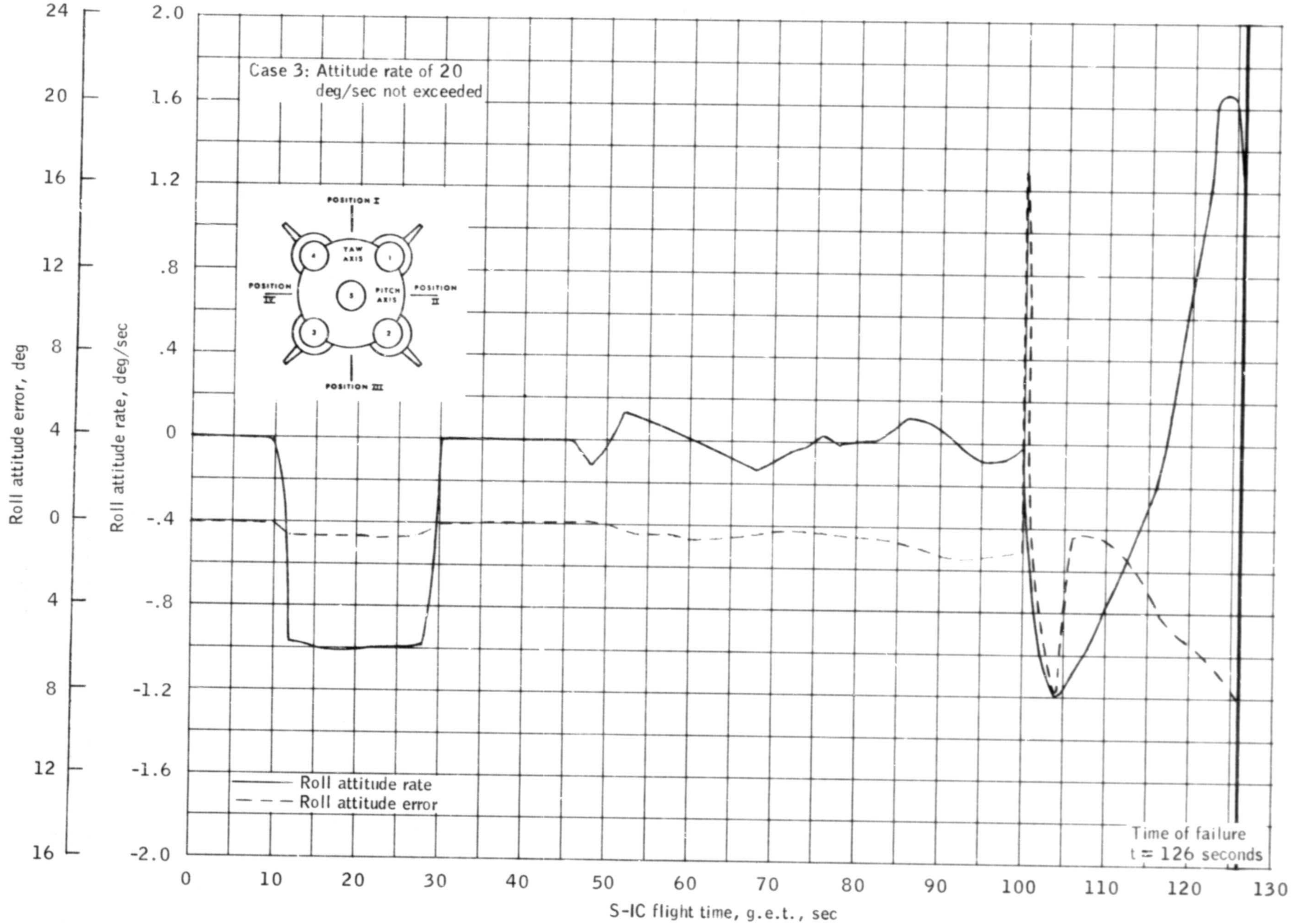
(a) Pitch attitude rate and pitch attitude error versus S-IC flight time.

Figure 2.- Case 3: S-IC engines 1 and 5 out at 46 seconds ground elapsed time.



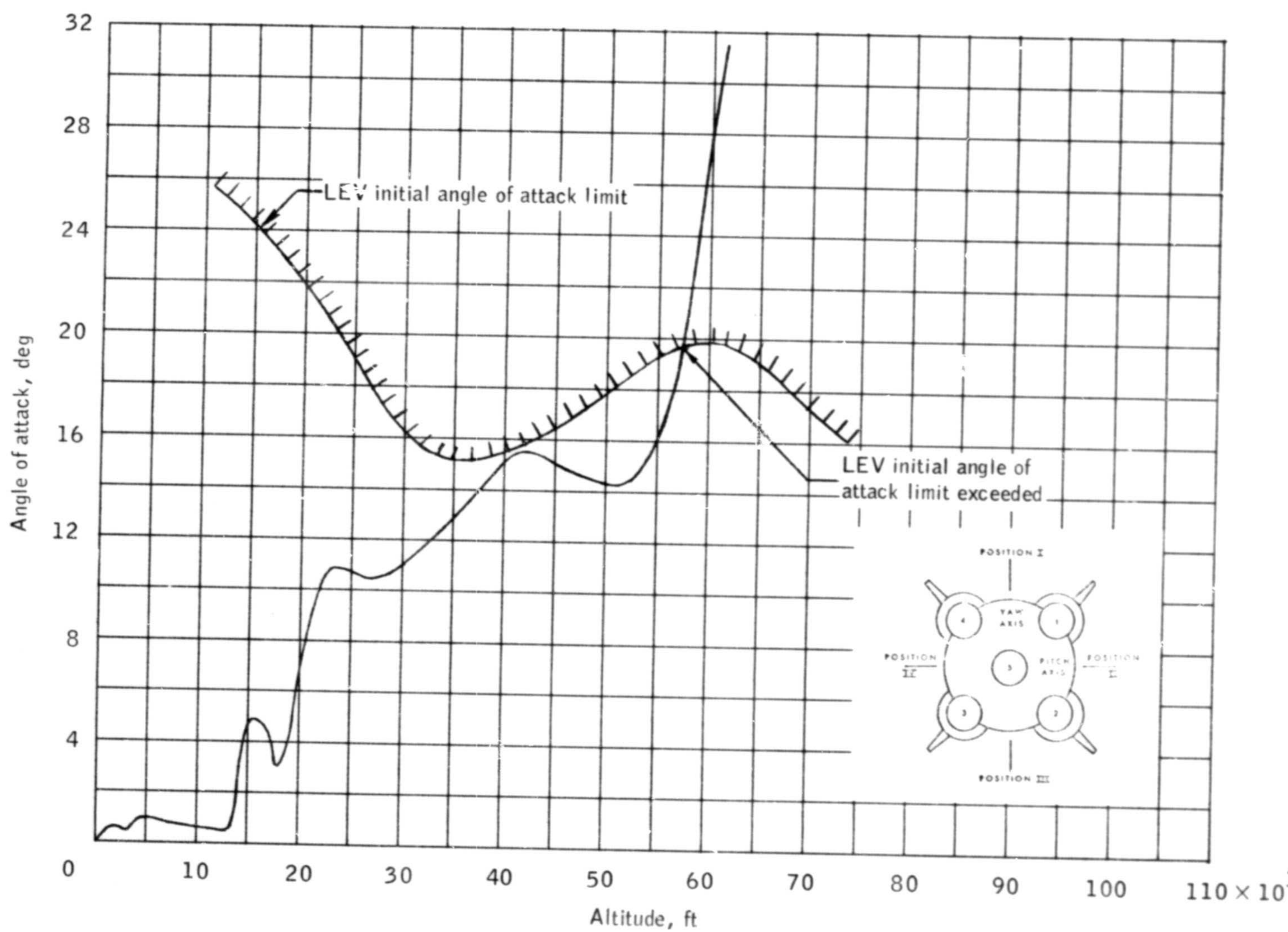
(b) Yaw attitude rate and yaw attitude error versus S-IC flight time.

Figure 2.- Continued.



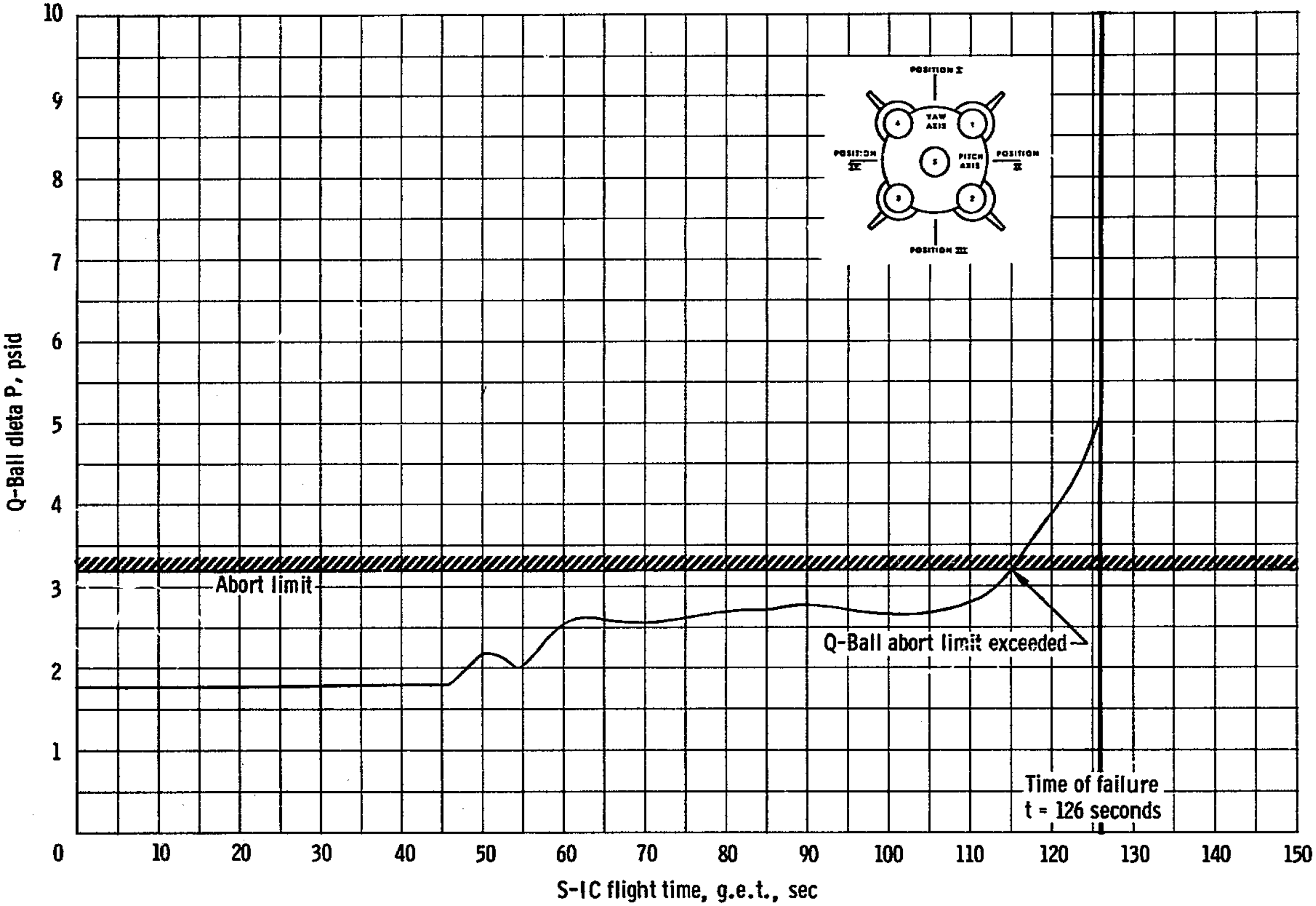
(c) Roll attitude rate and roll attitude error versus S-IC flight time.

Figure 2.- Continued.



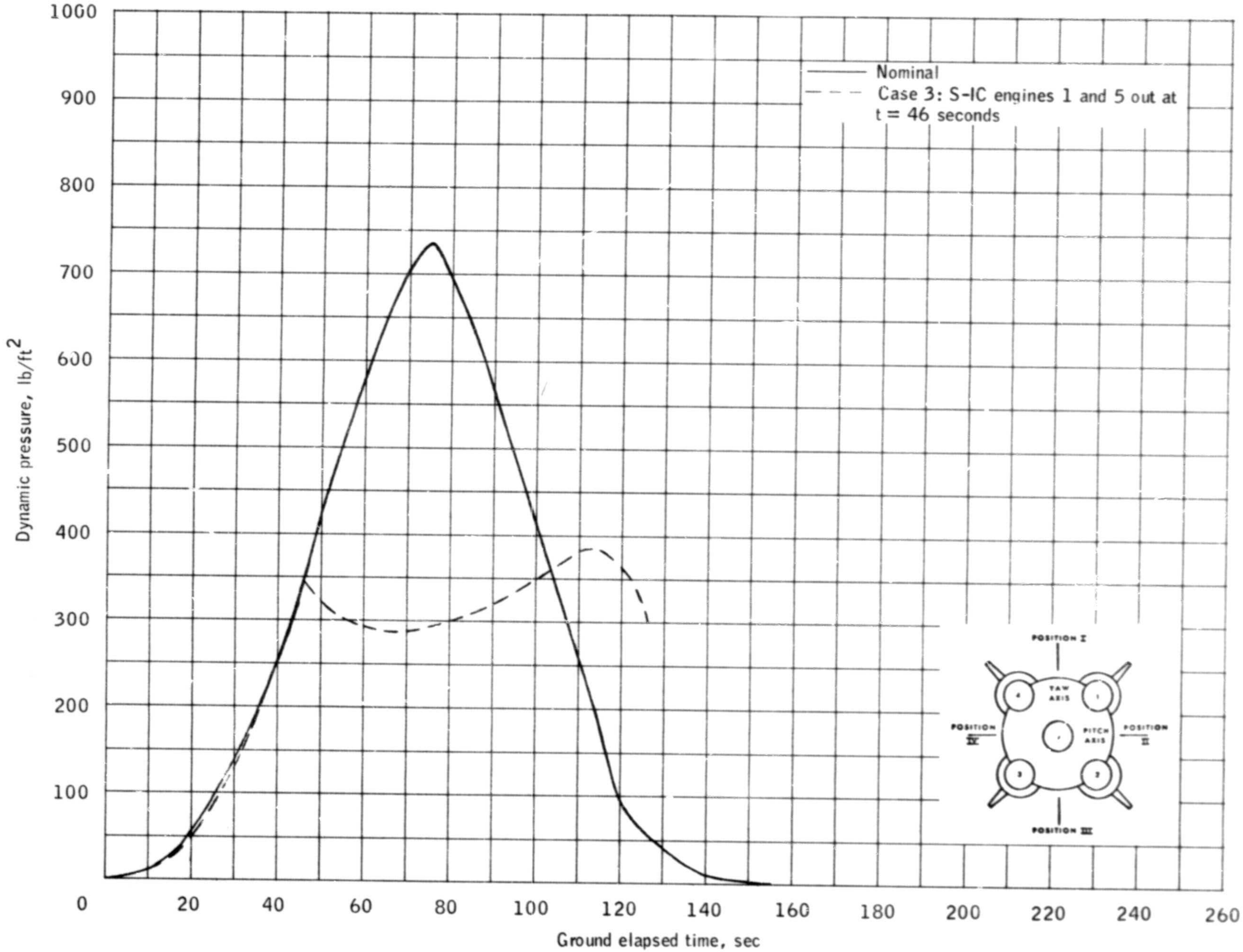
(d) Angle of attack versus altitude.

Figure 2.- Continued.



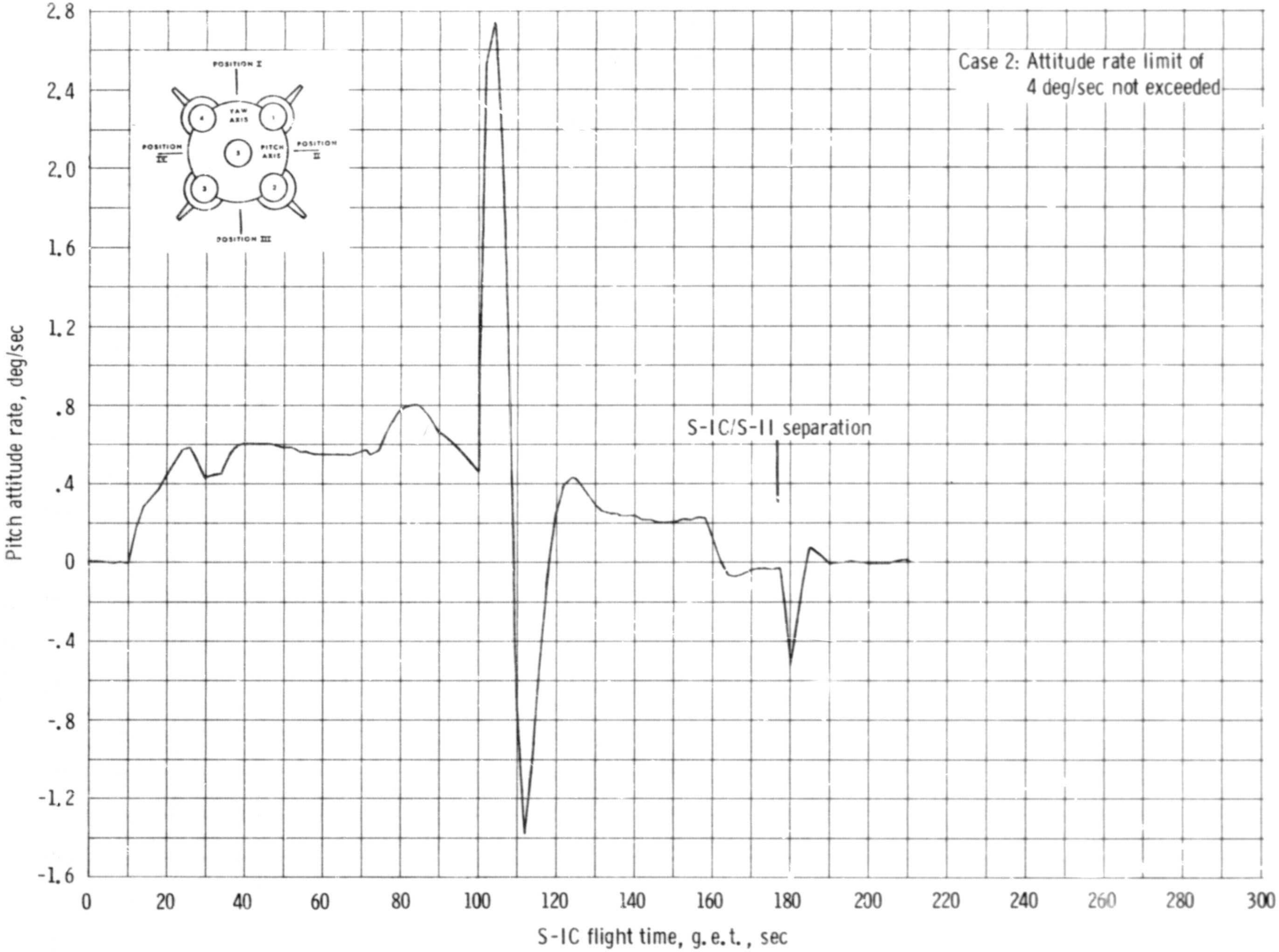
(e) Q-Ball reading versus S-IC flight time.

Figure 2. - Continued.



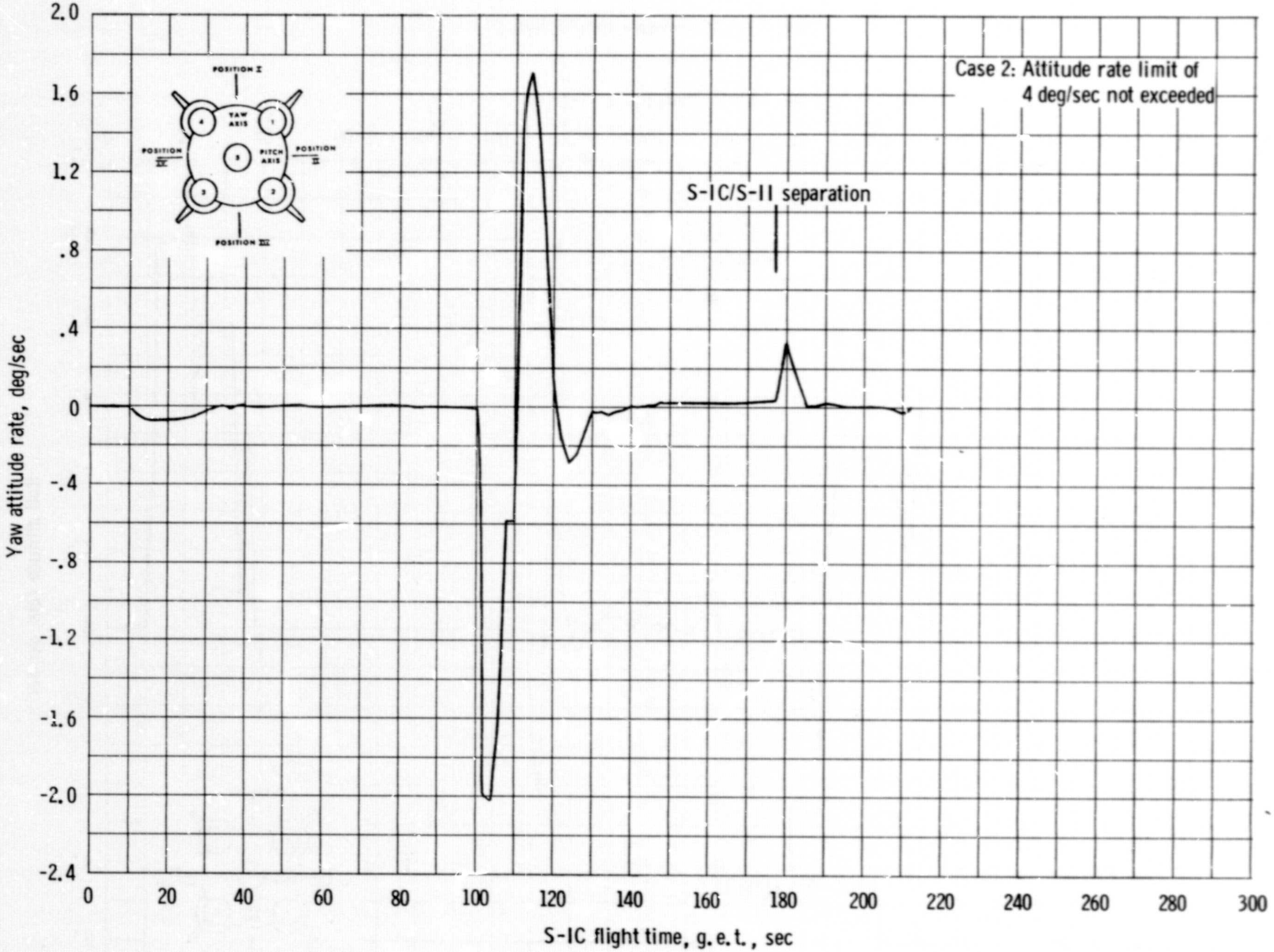
(f) Dynamic pressure versus time.

Figure 2.- Concluded.



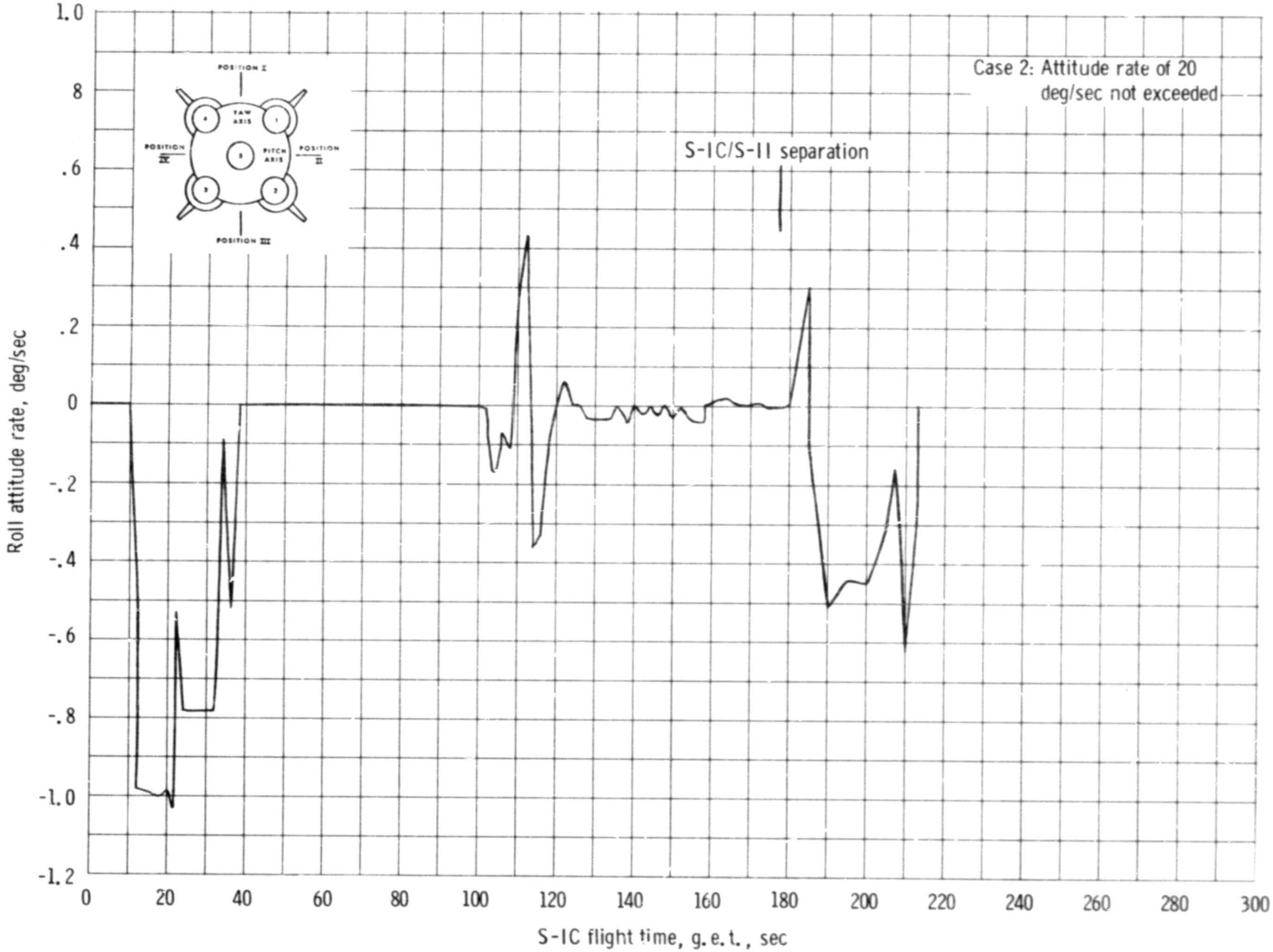
(a) Pitch attitude rate versus S-IC flight time.

Figure 3. - Case 2: S-IC engines 1 and 5 out at 100 seconds ground elapsed time.



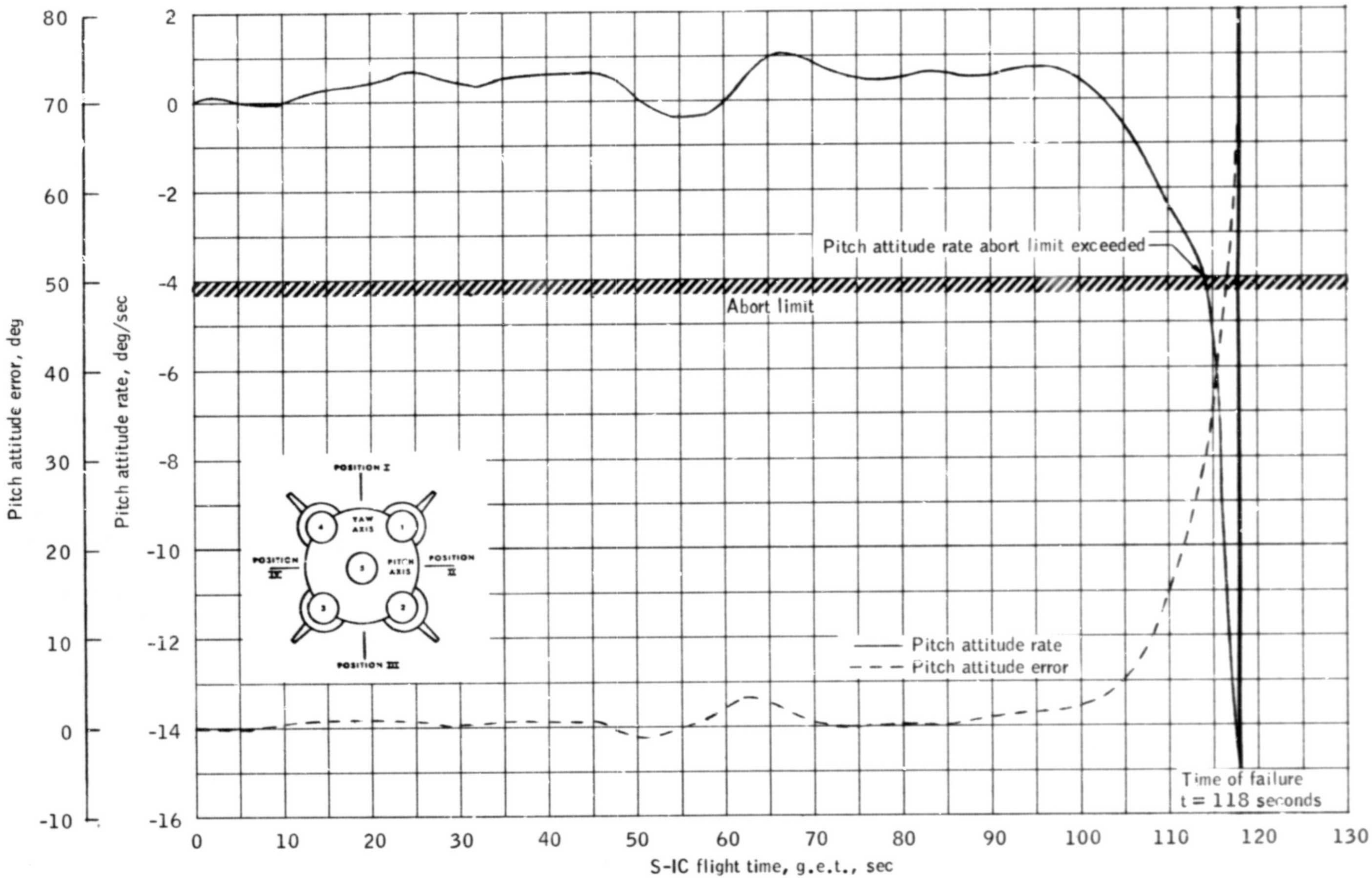
(b) Yaw attitude rate versus S-IC flight time.

Figure 3. - Continued.



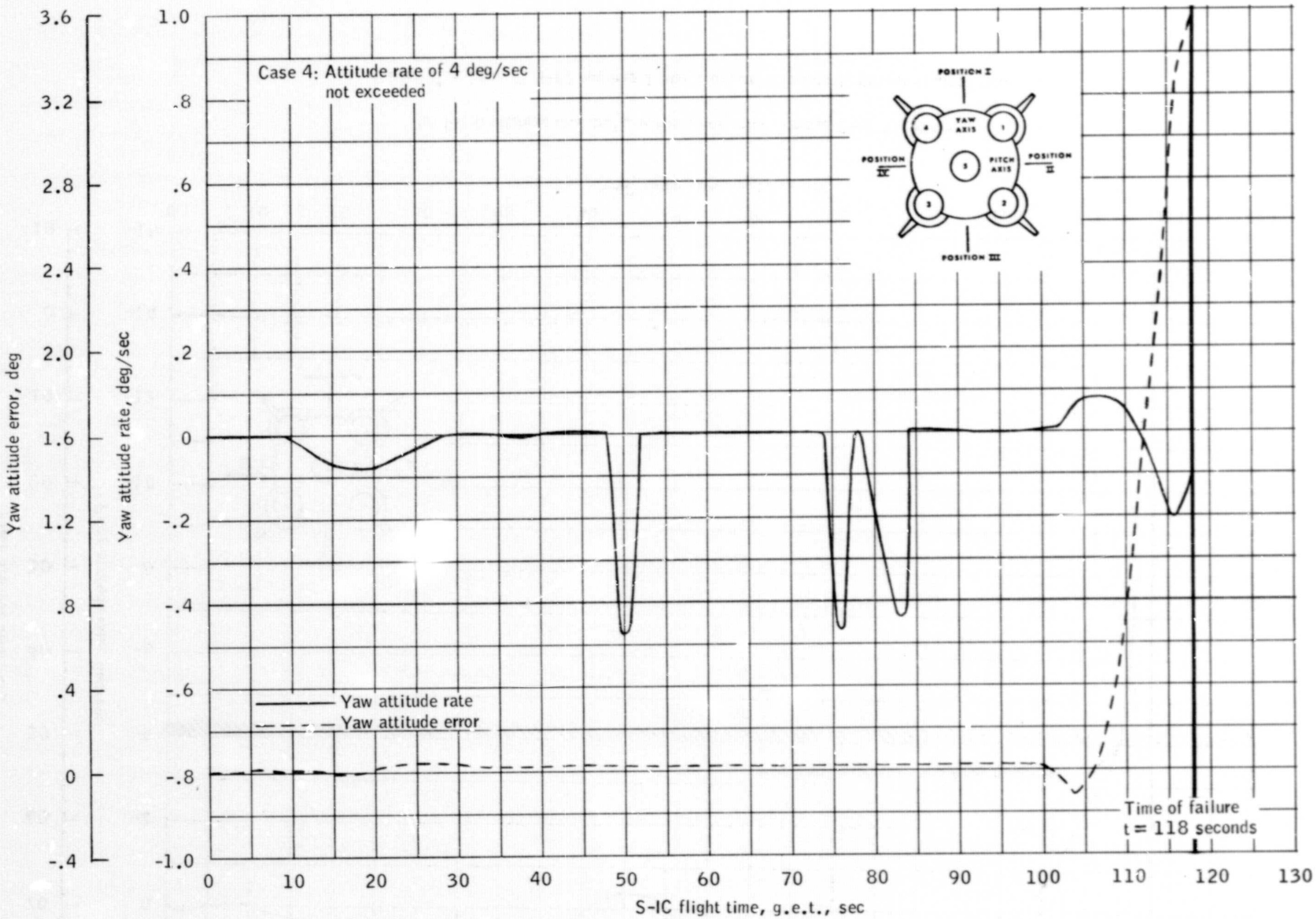
(c) Roll attitude rate versus S-IC flight time.

Figure 3. - Concluded.



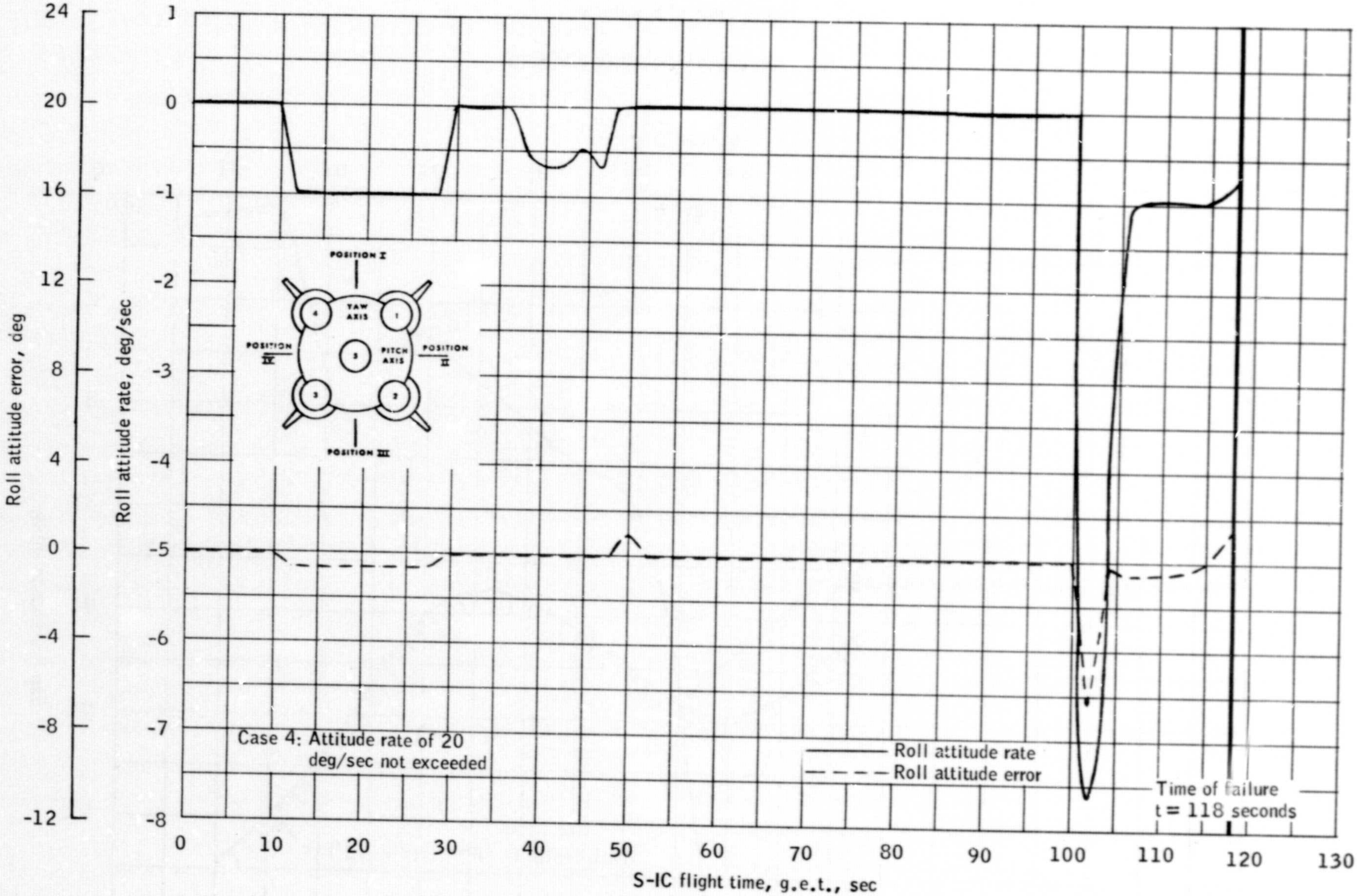
(a) Pitch attitude rate and pitch attitude error versus S-IC flight time.

Figure 4.- Case 4: S-IC engines 1 and 3 out at 46 seconds ground elapsed time.



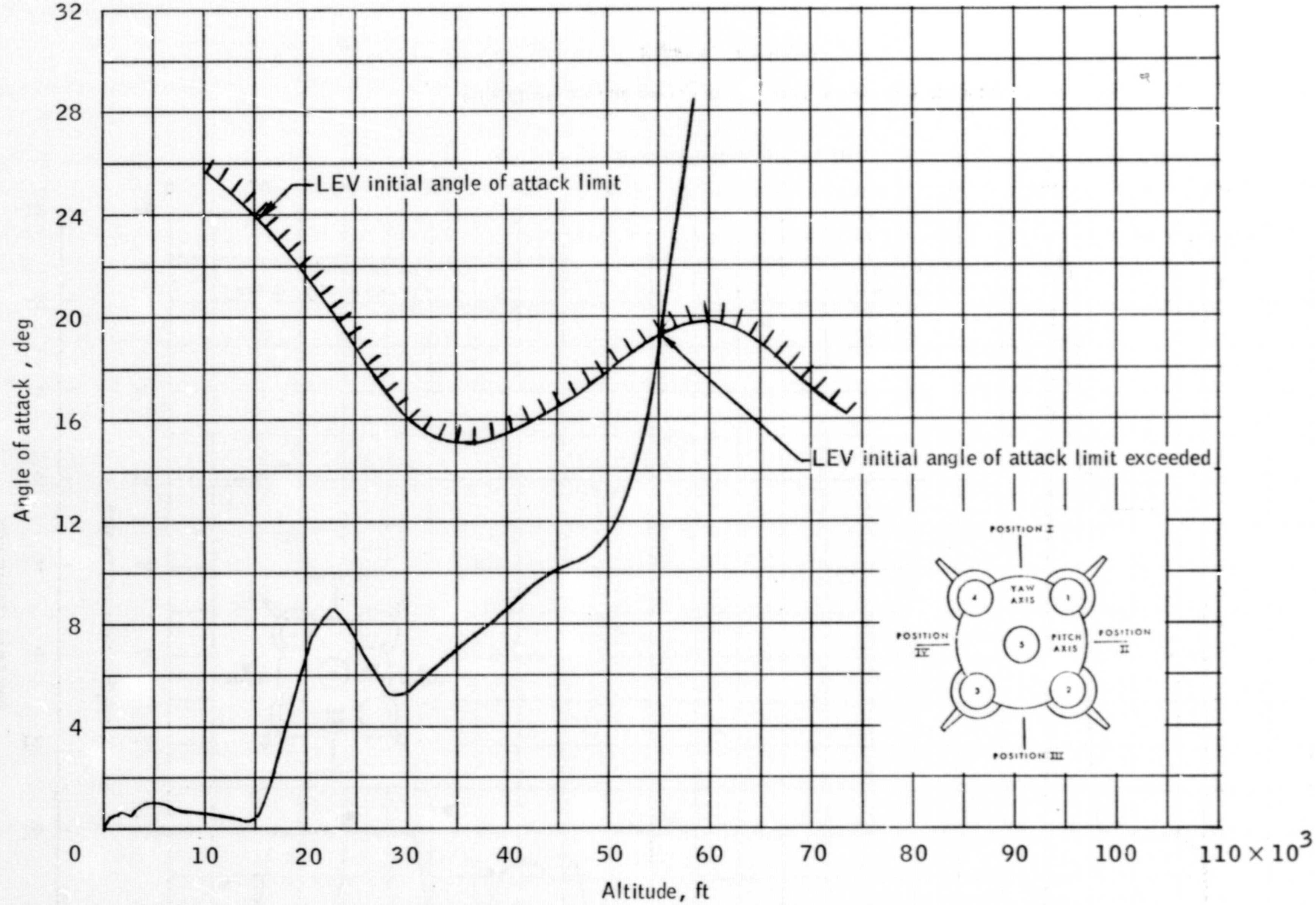
(b) Yaw attitude rate and yaw attitude error versus S-IC flight time.

Figure 4.- Continued.



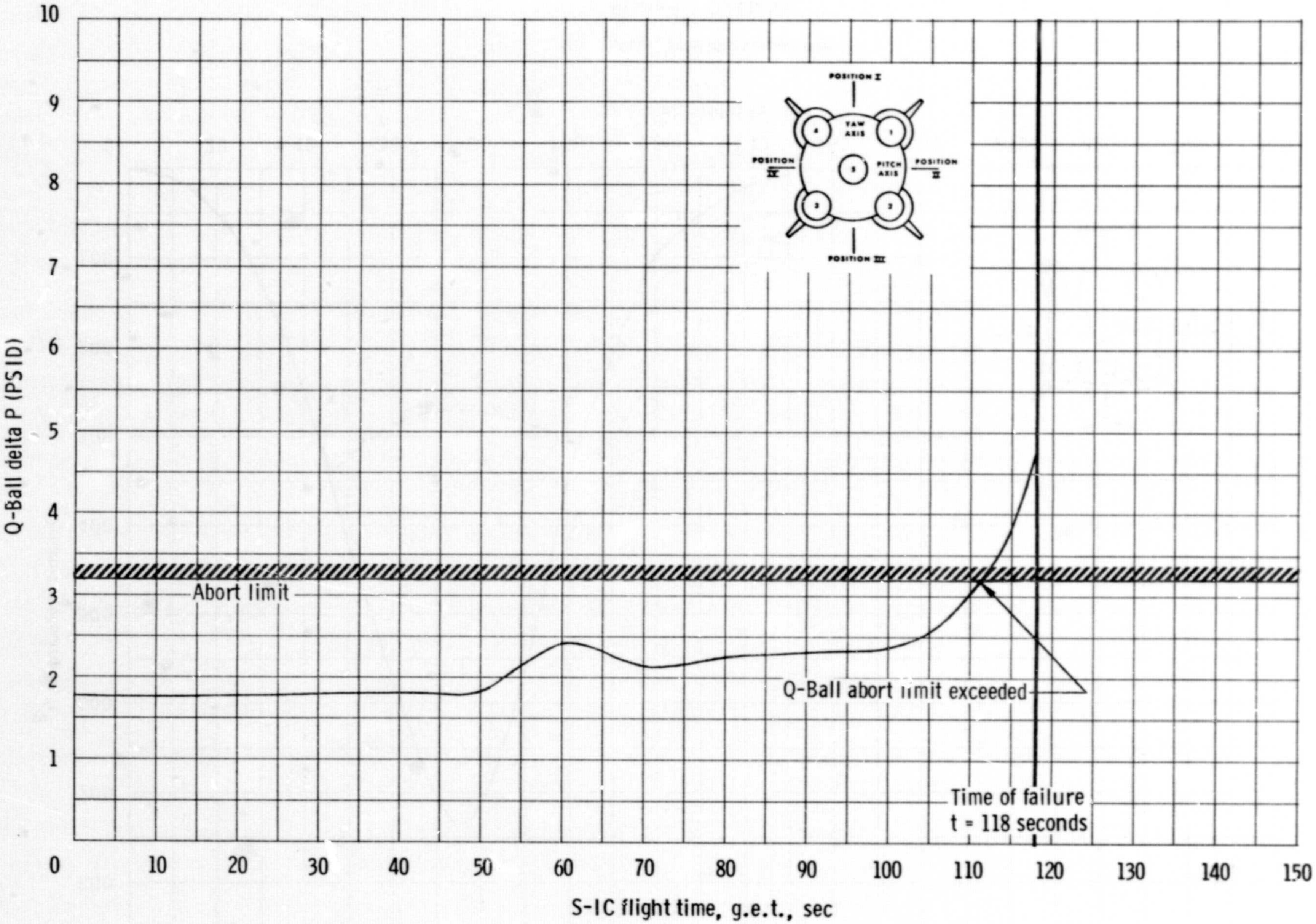
(c) Roll attitude rate and roll attitude error versus S-IC flight time.

Figure 4.- Continued.



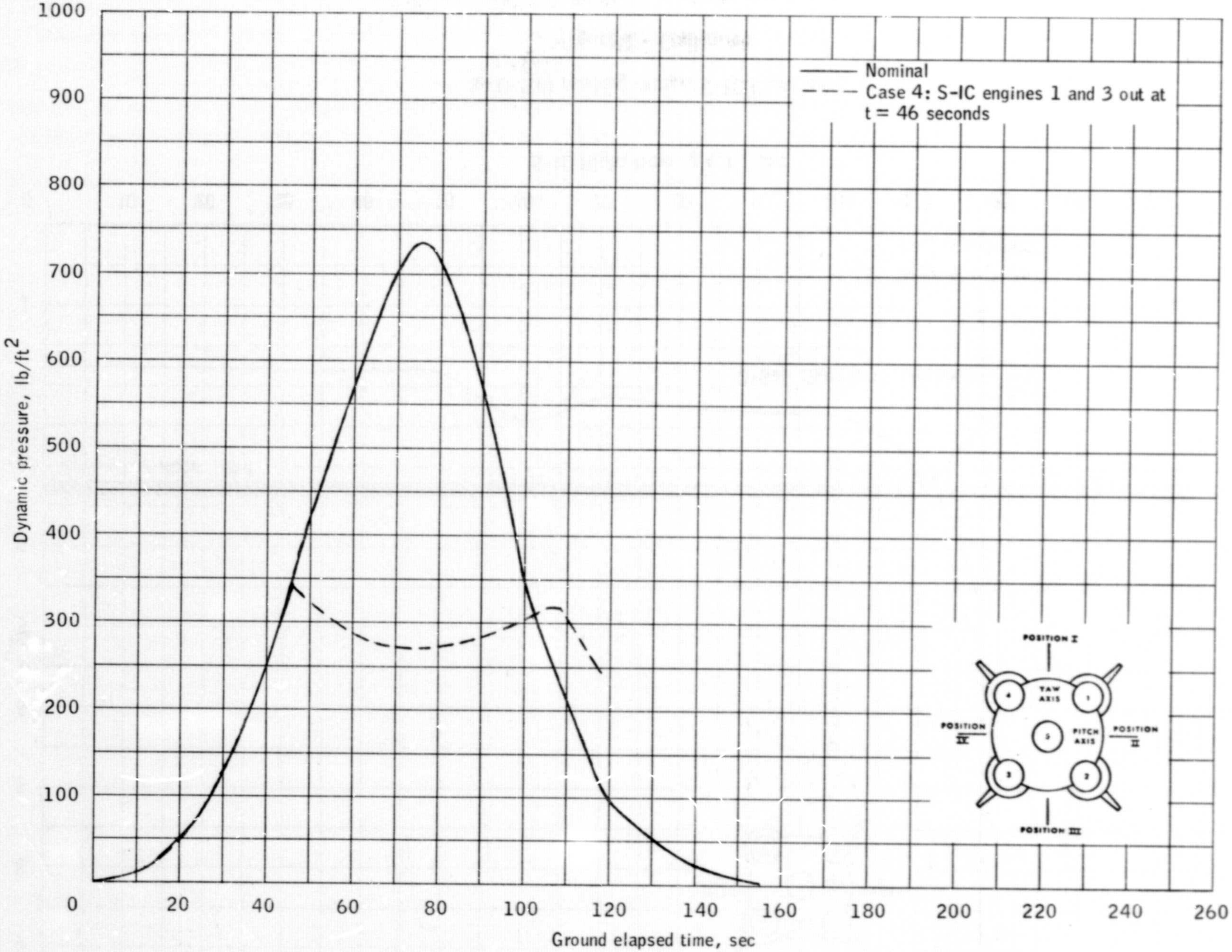
(d) Angle of attack versus altitude.

Figure 4.- Continued.



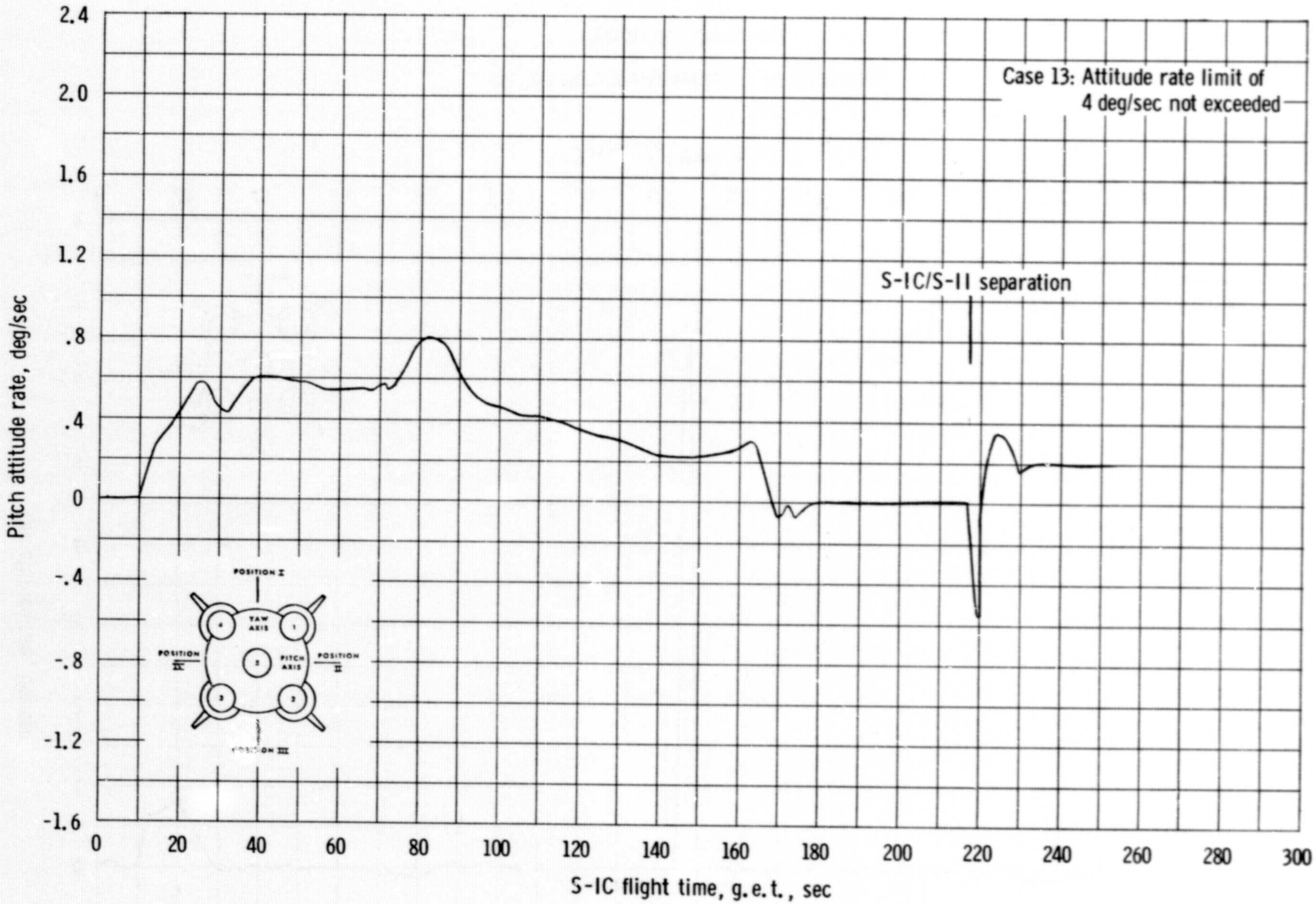
(e) Q-Ball reading versus S-IC flight time.

Figure 4. - Continued.



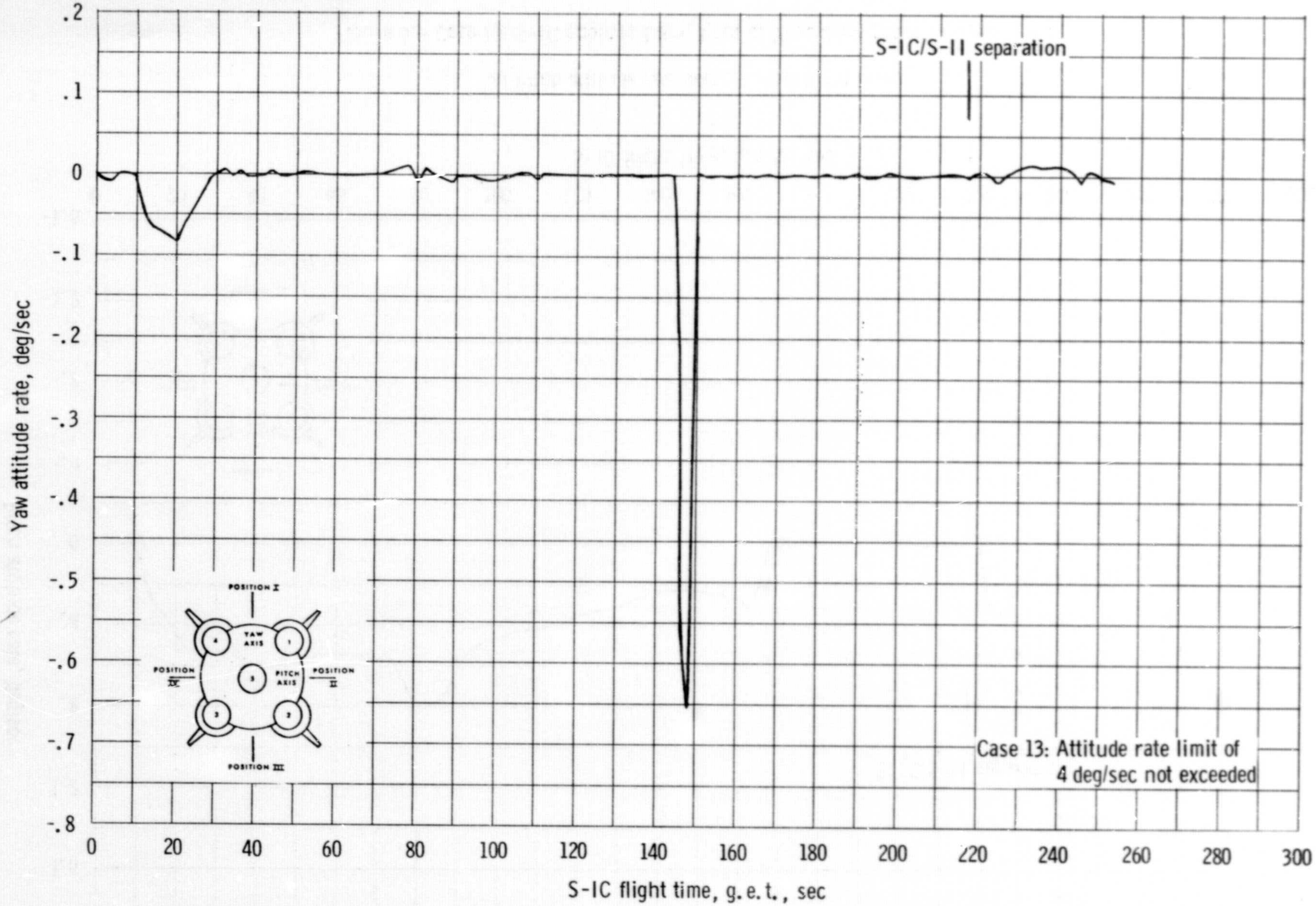
(f) Dynamic pressure versus time.

Figure 4.- Concluded.



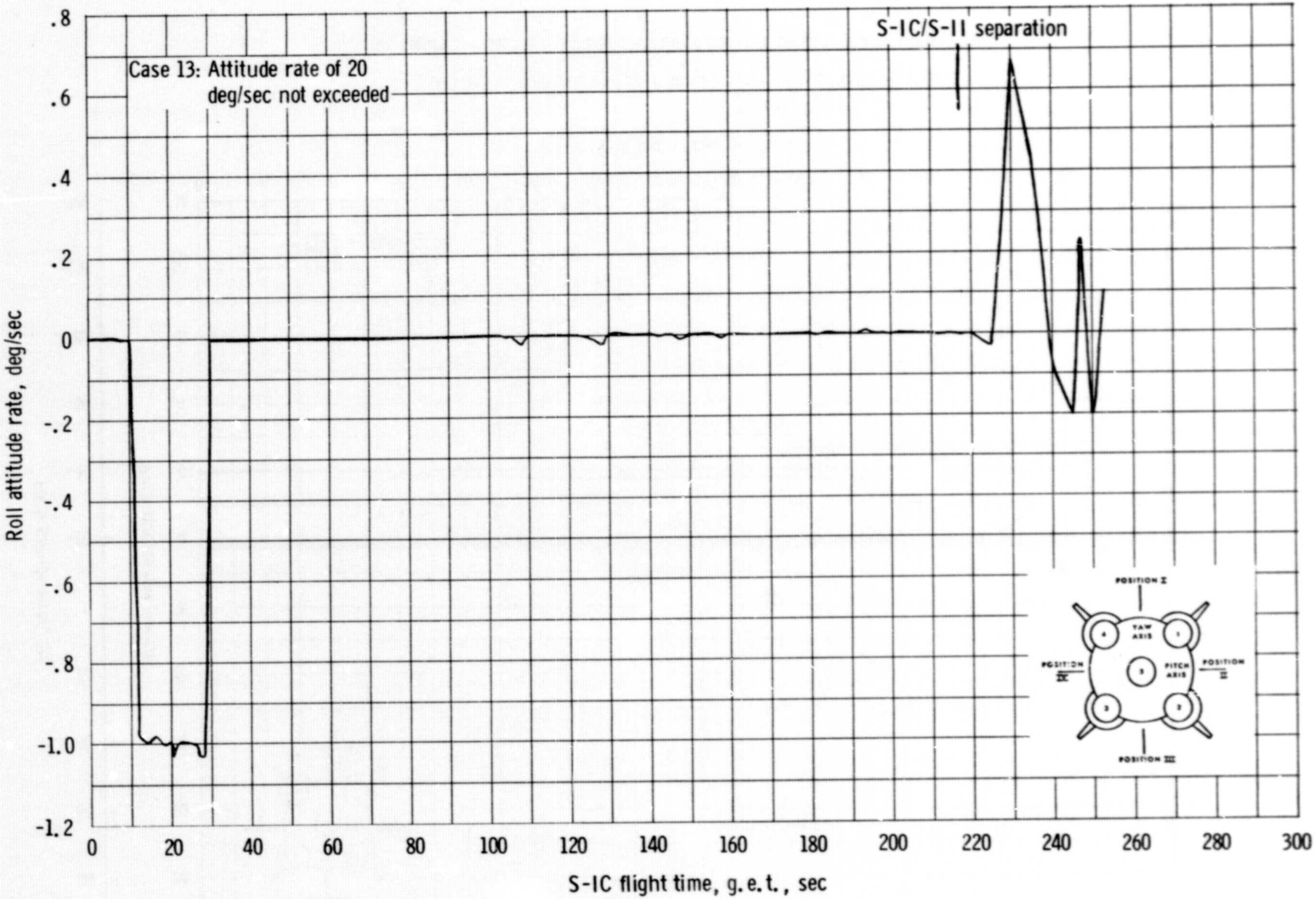
(a) Pitch attitude rate versus S-IC flight time.

Figure 5. - Case 13: S-IC engines 1 and 3 out at 80 seconds ground elapsed time.



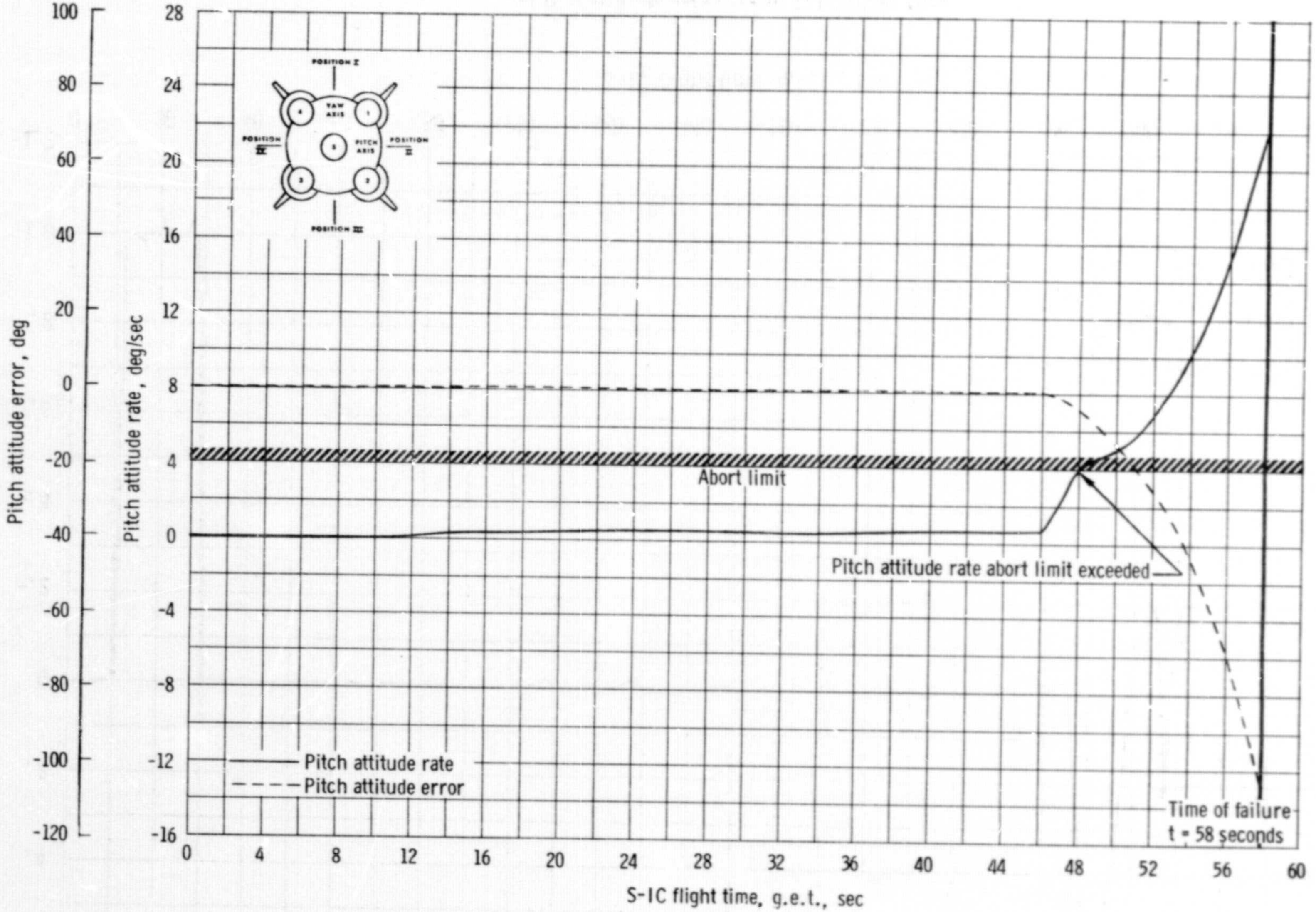
(b) Yaw attitude rate versus S-IC flight time.

Figure 5. - Continued.



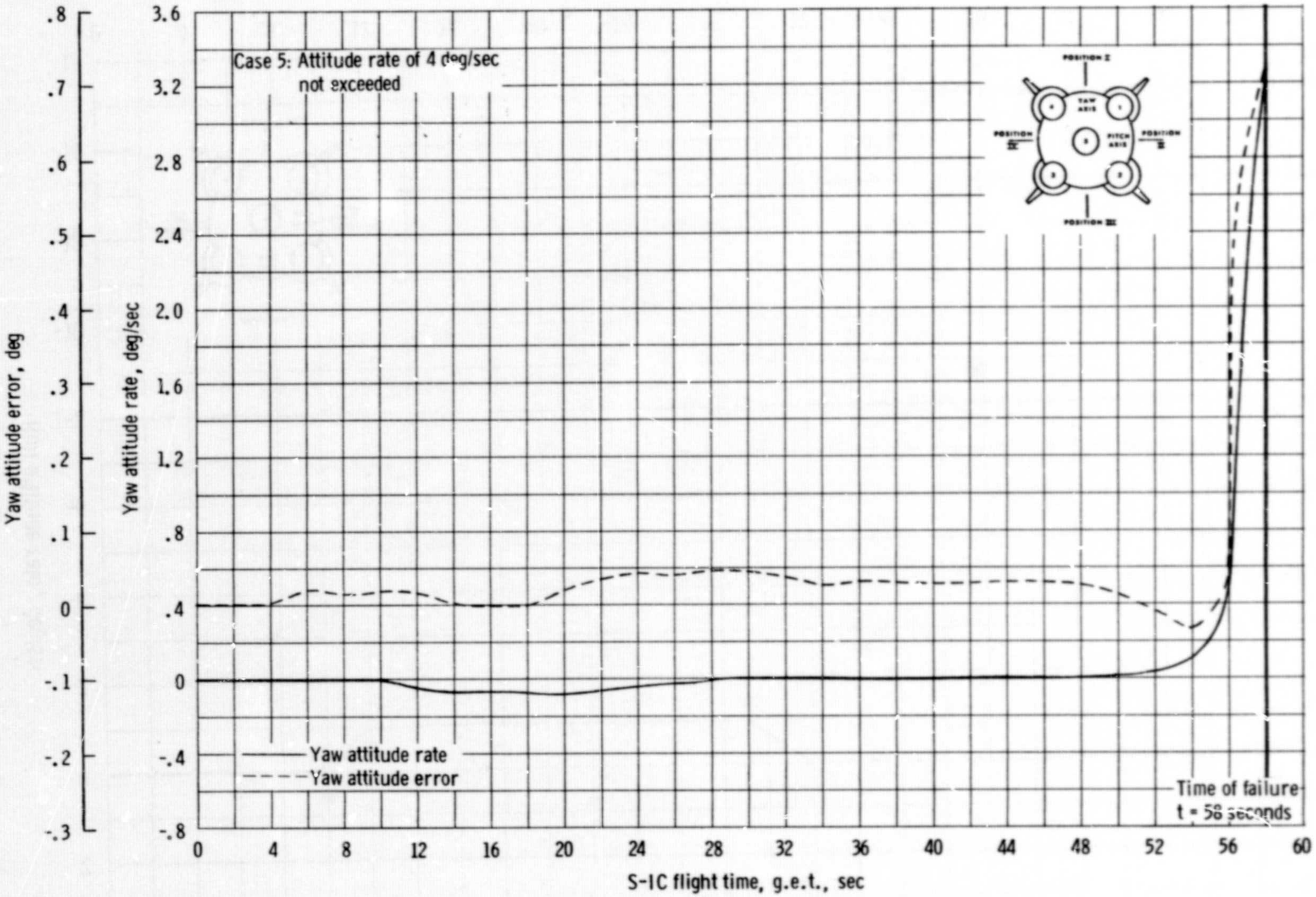
(c) Roll attitude rate versus S-IC flight time.

Figure 5. - Concluded.



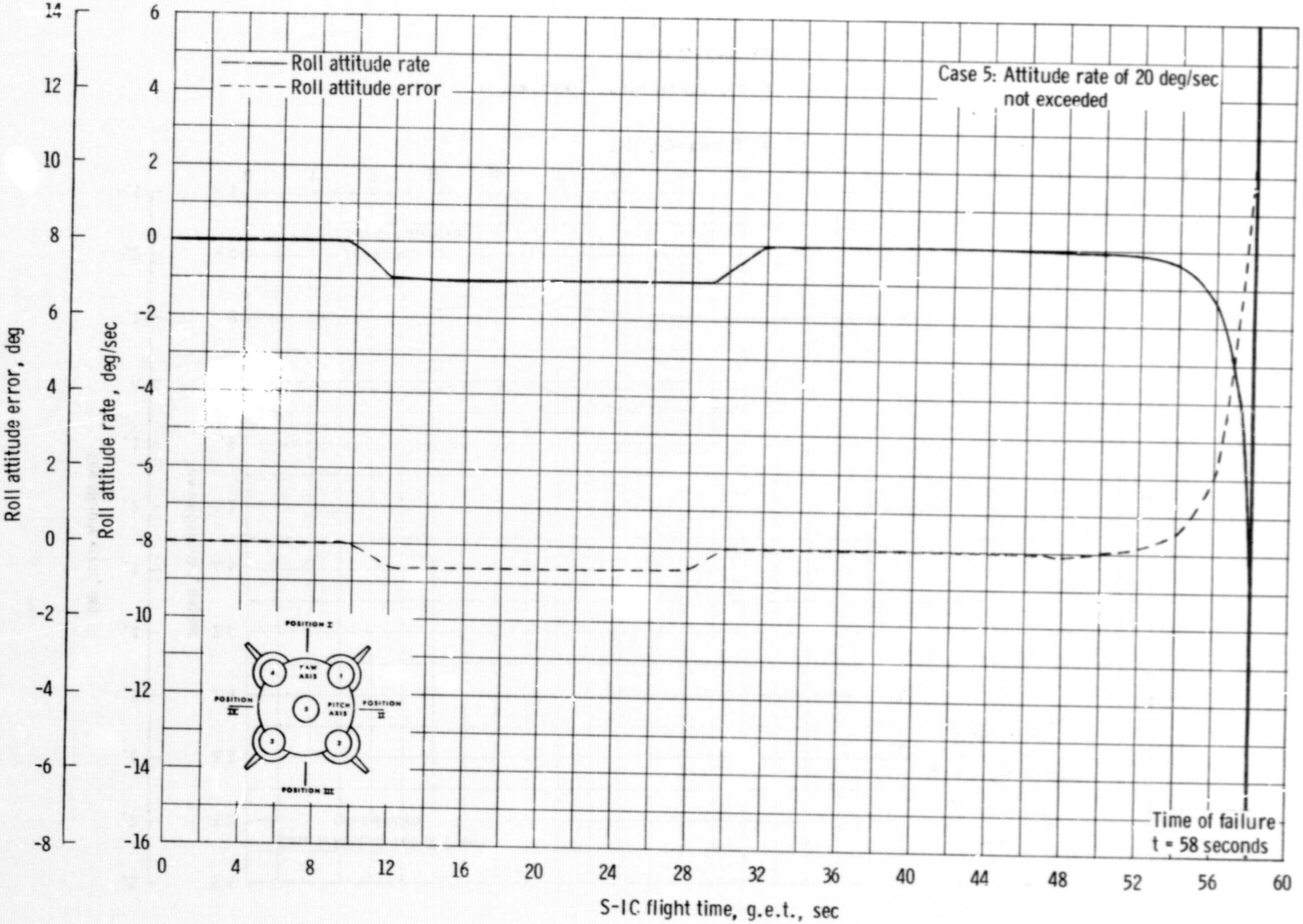
(a) Pitch attitude rate and pitch attitude error versus S-IC flight time.

Figure 6. - Case 5: S-IC engines 1 and 4 out at 46 seconds ground elapsed time.



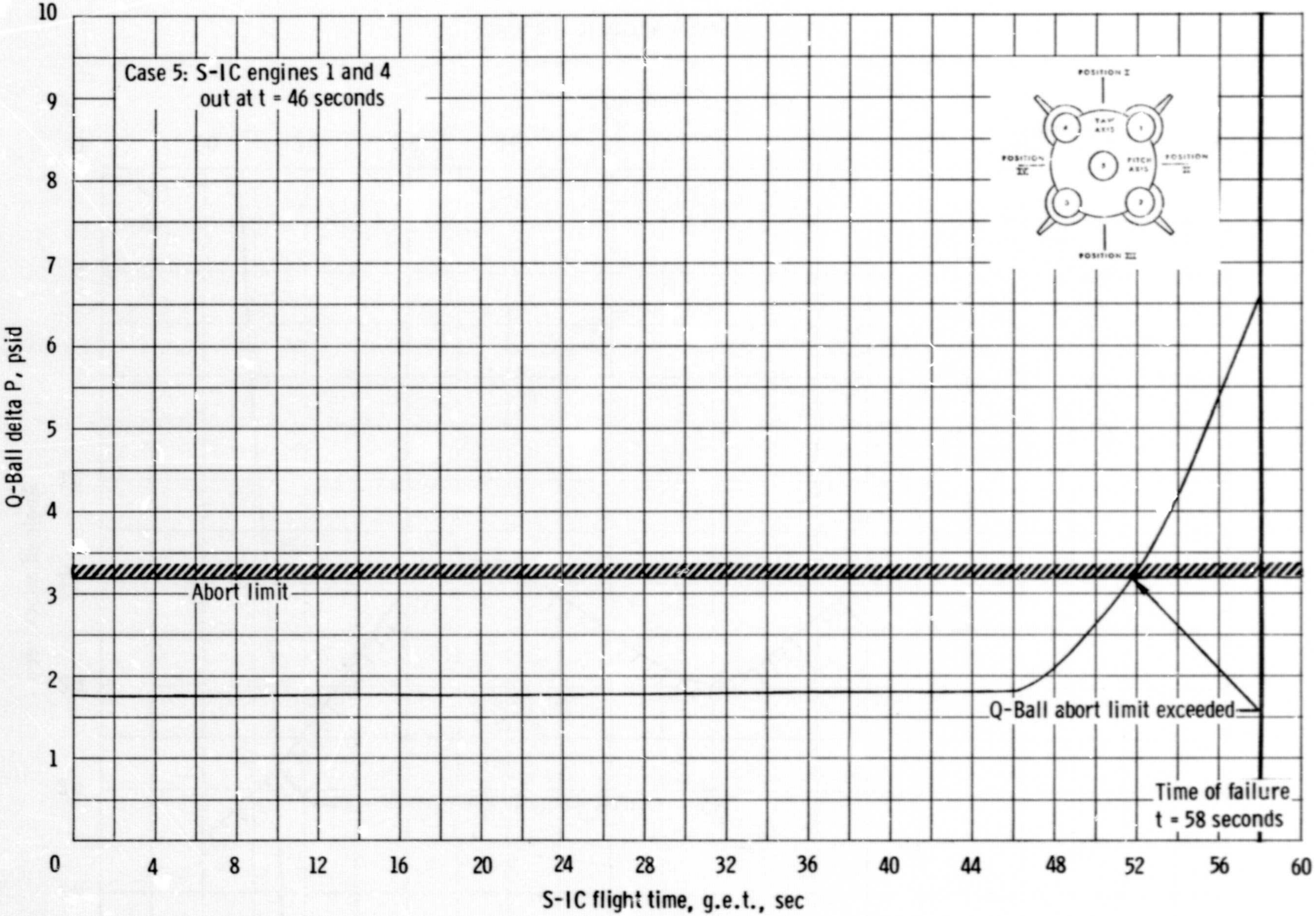
(b) Yaw attitude rate and yaw attitude error versus S-IC flight time.

Figure 6. - Continued.



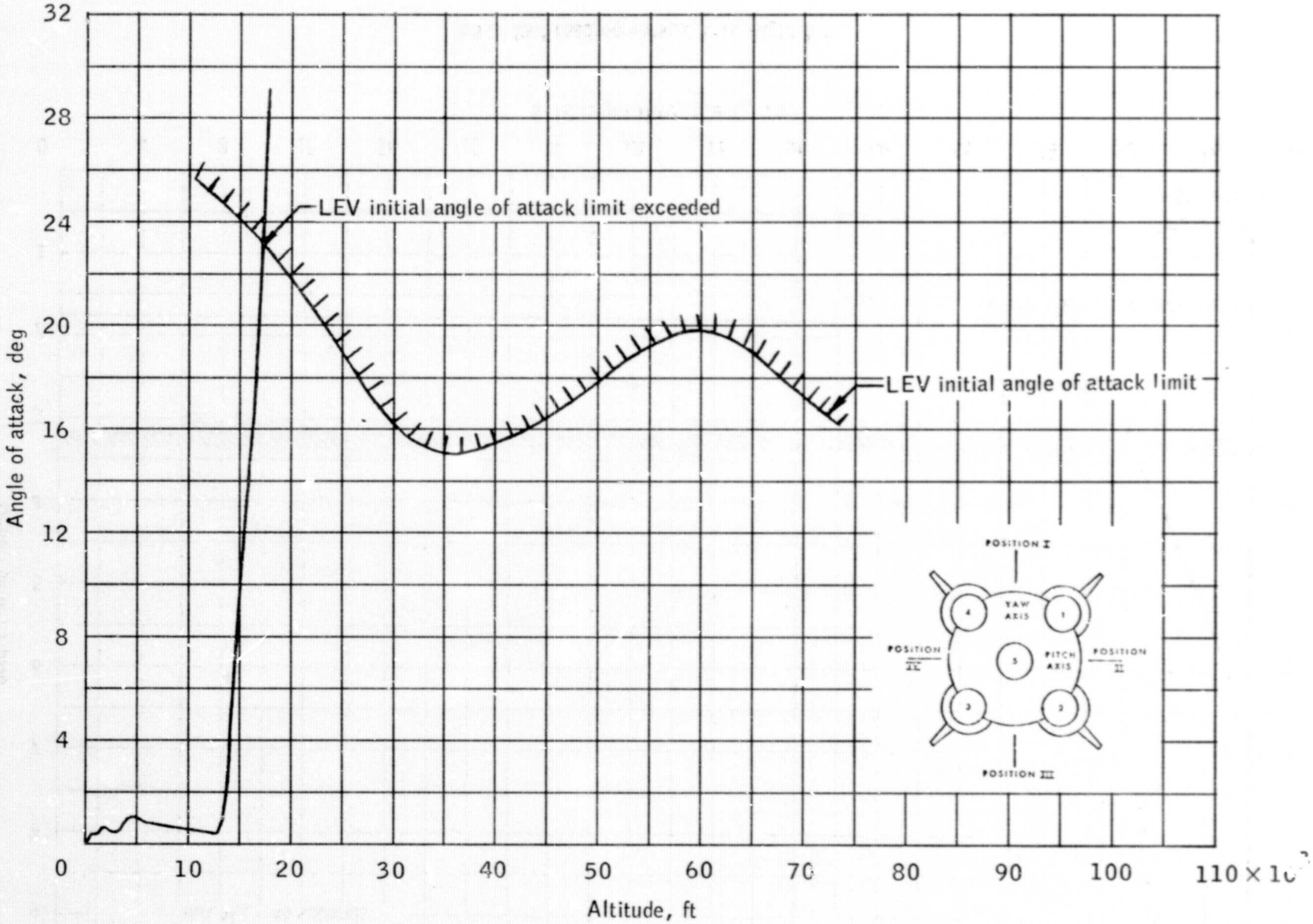
(c) Roll attitude rate and roll attitude error versus S-IC flight time.

Figure 6. - Continued.



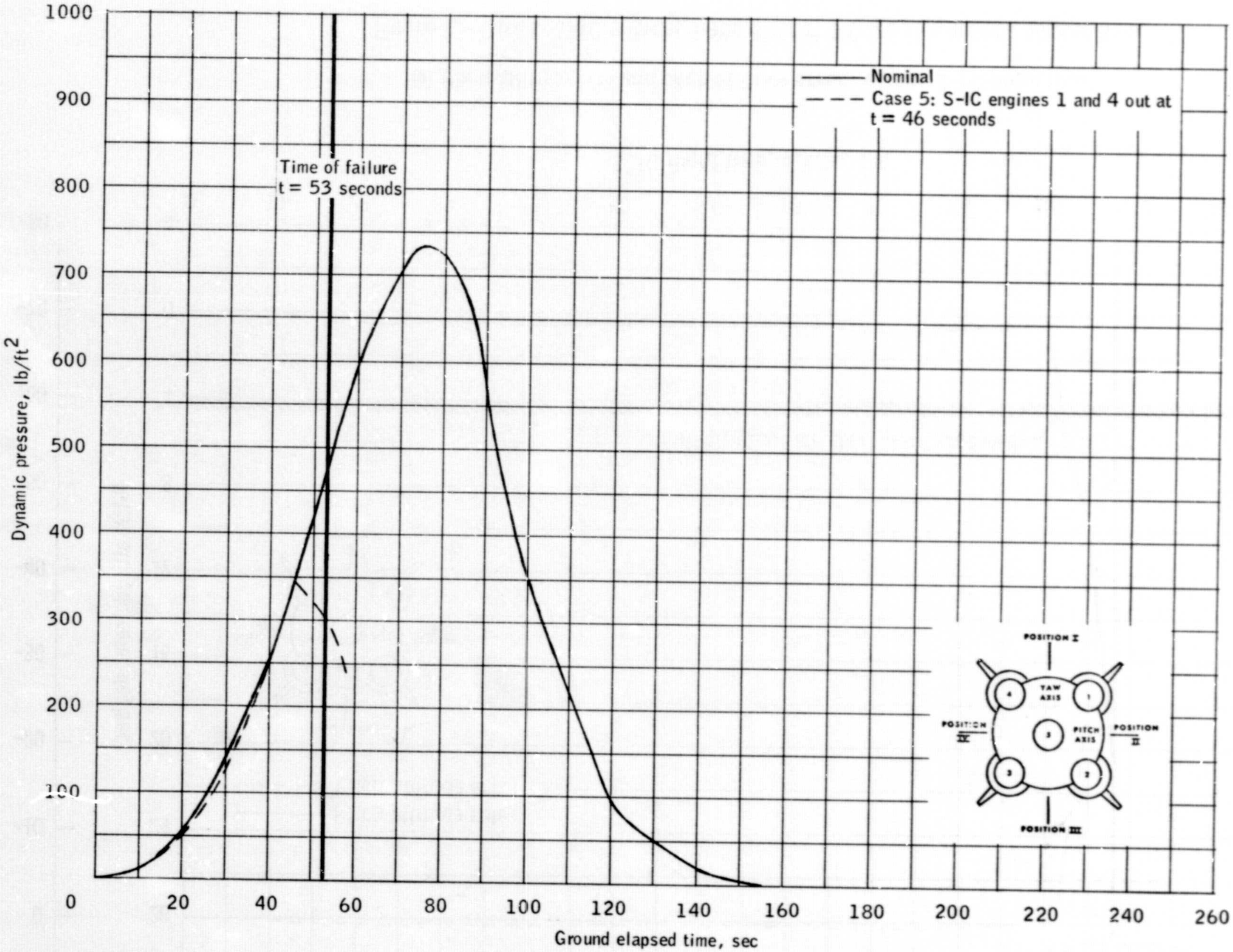
(d) Q-Ball reading versus S-IC flight time.

Figure 6. - Continued.



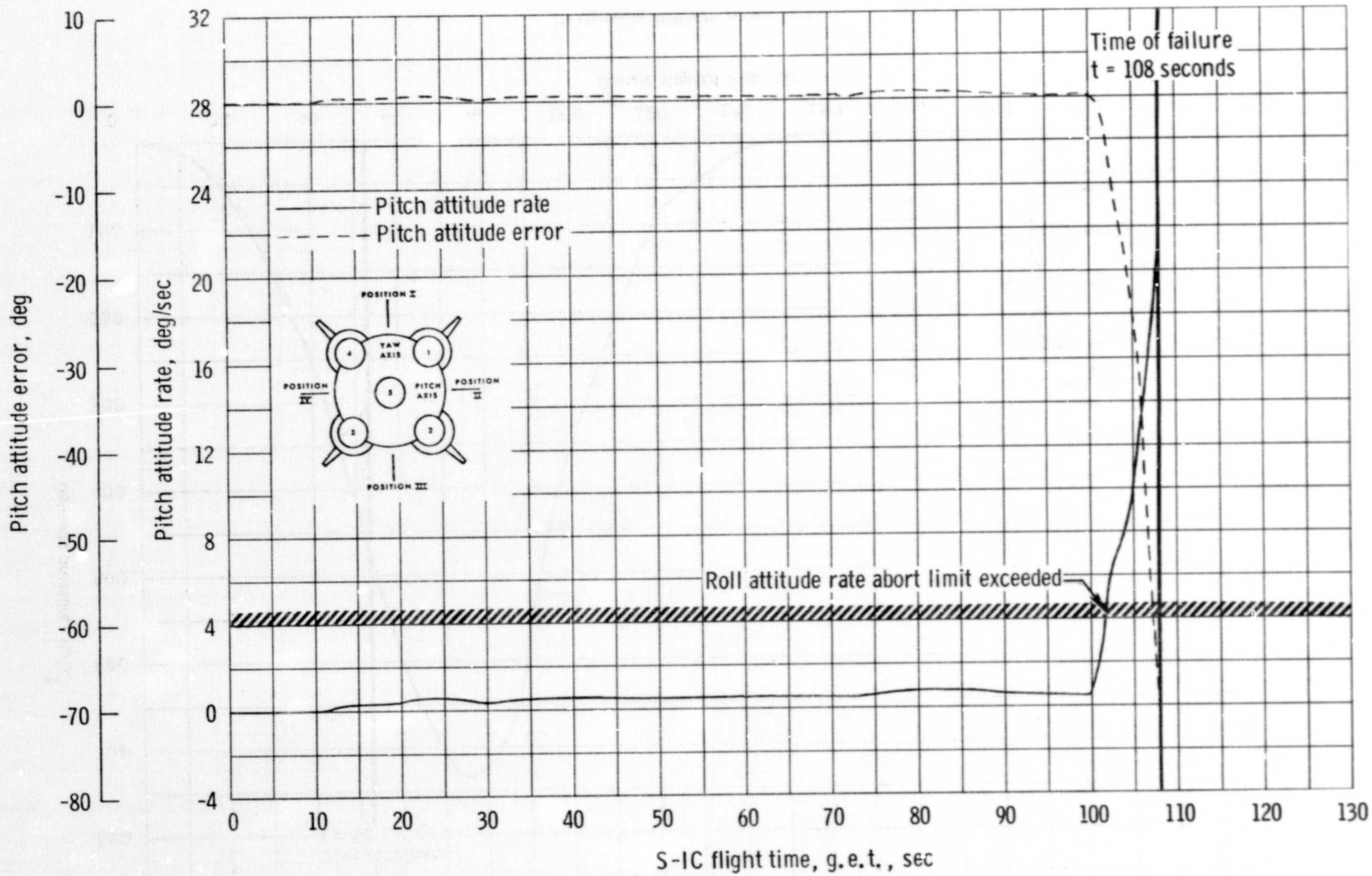
(e) Angle of attack versus altitude.

Figure 6.- Continued.



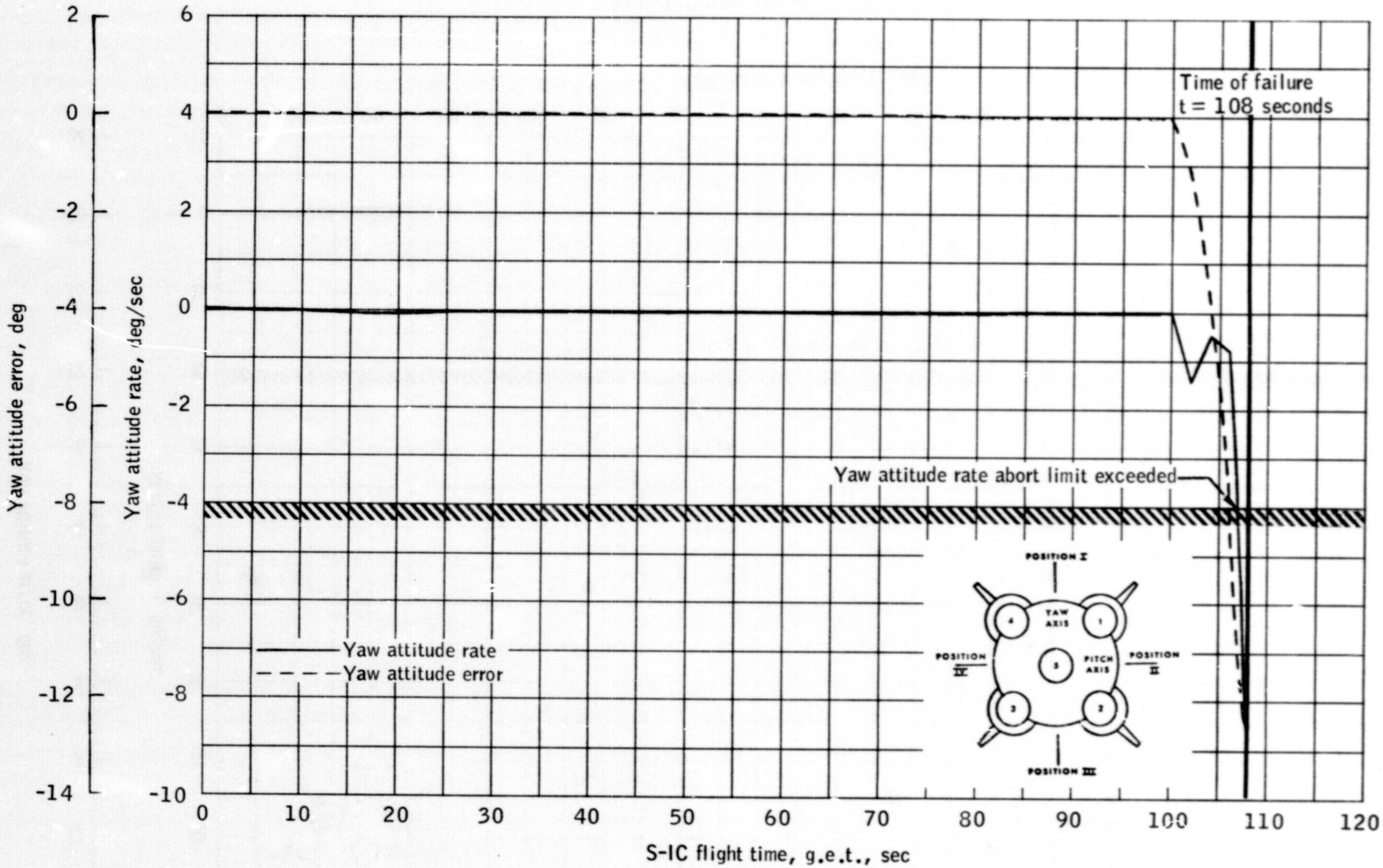
(f) Dynamic pressure versus time.

Figure 6.- Concluded.



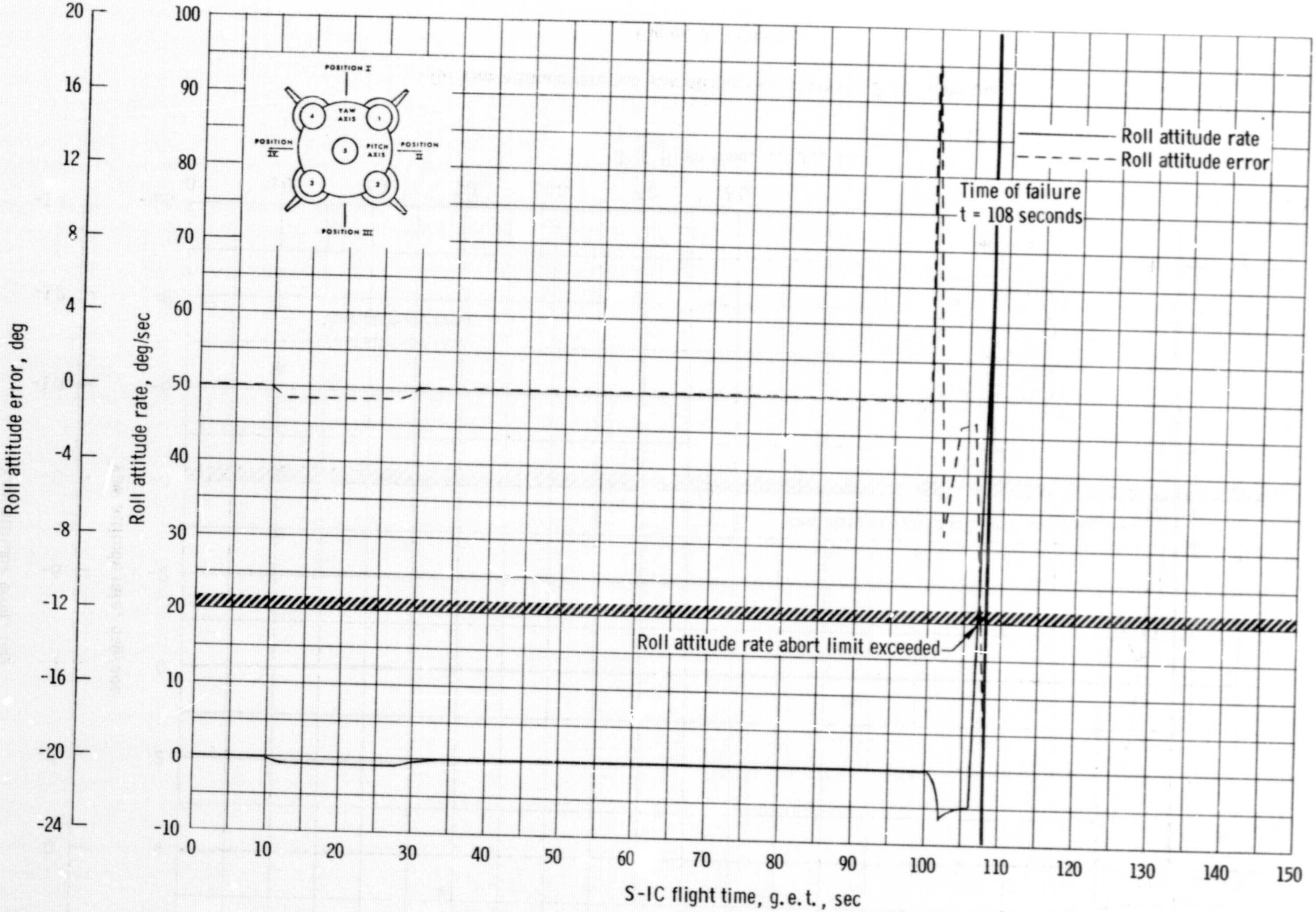
(a) Pitch attitude rate and pitch attitude error versus S-IC flight time.

Figure 7. - Case 8: S-IC engines 1 and 4 out at 100 seconds ground elapsed time.



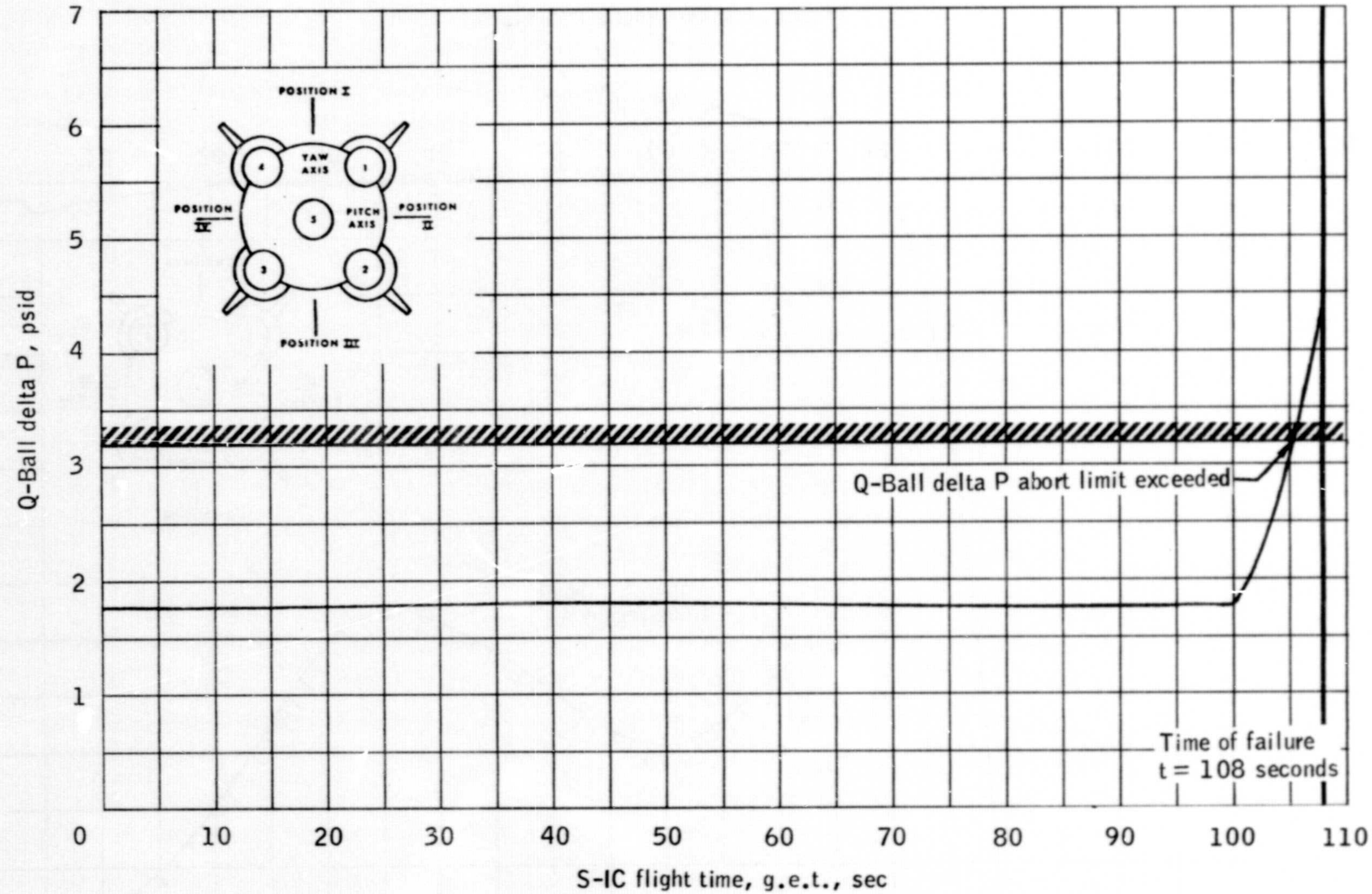
(b) Yaw attitude rate and yaw attitude error versus S-IC flight time.

Figure 7.- Continued.



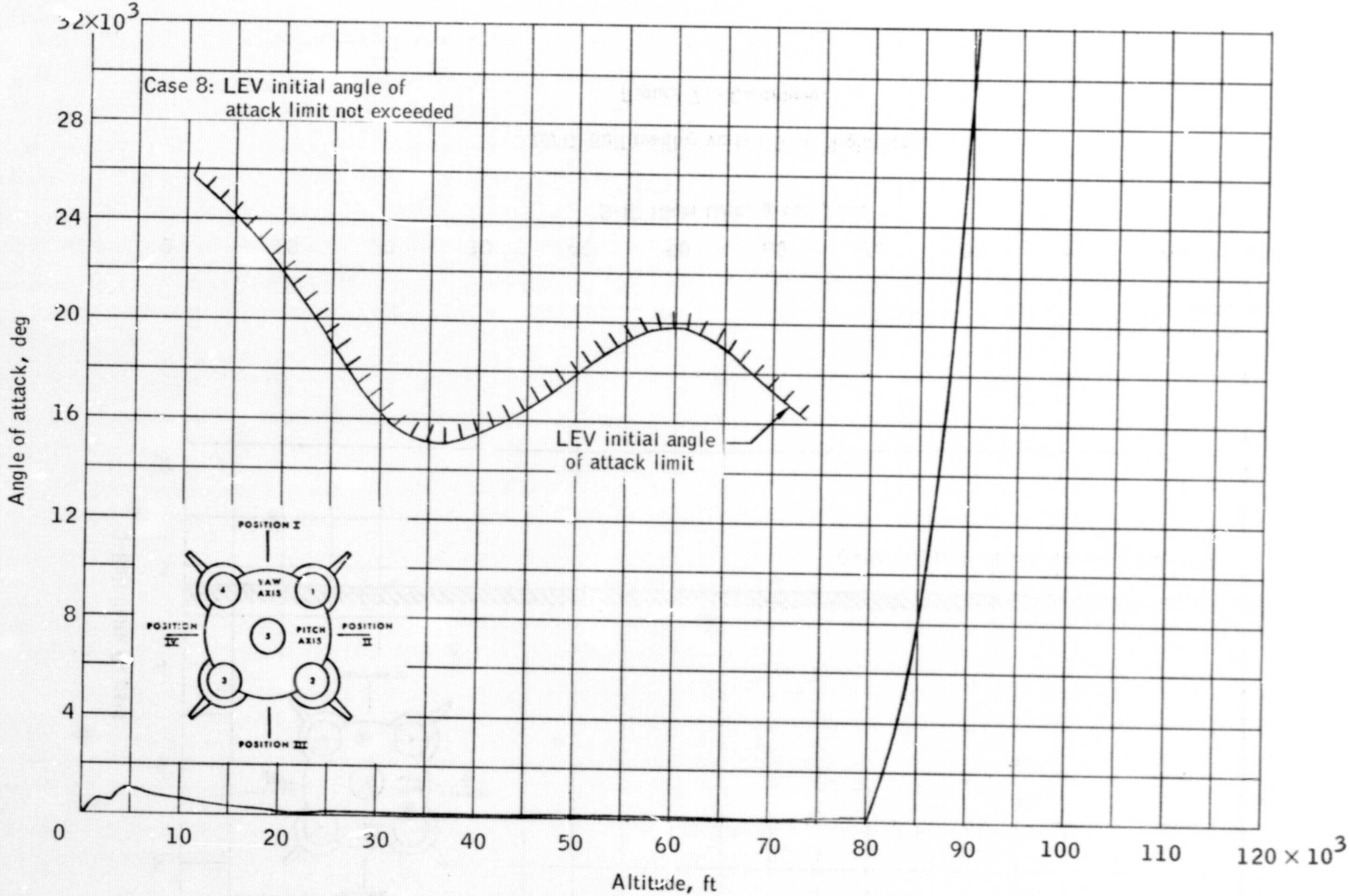
(c) Roll attitude rate and roll attitude error.

Figure 7. - Continued.



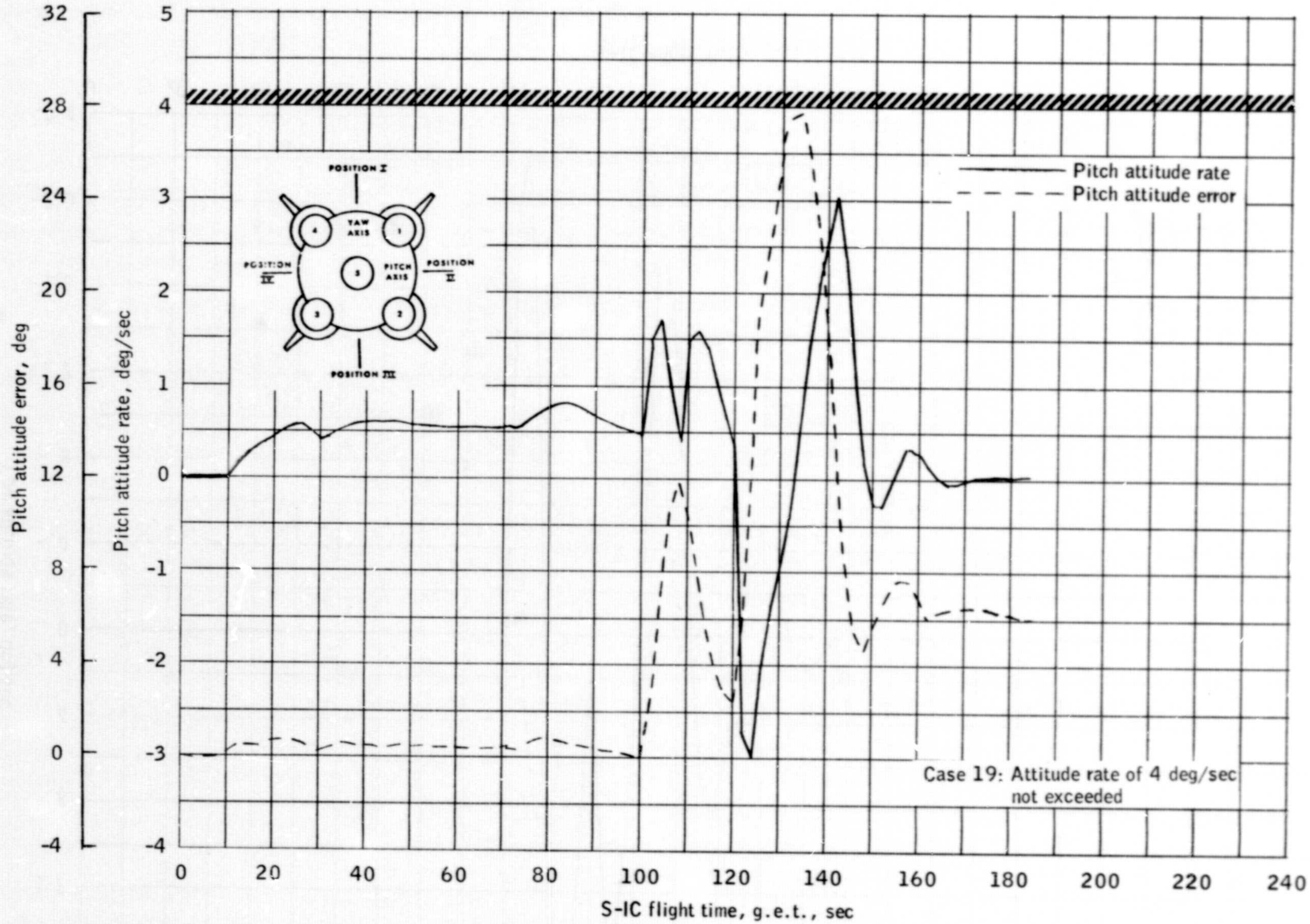
(d) Q-Ball reading versus S-IC flight time.

Figure 7.- Continued.



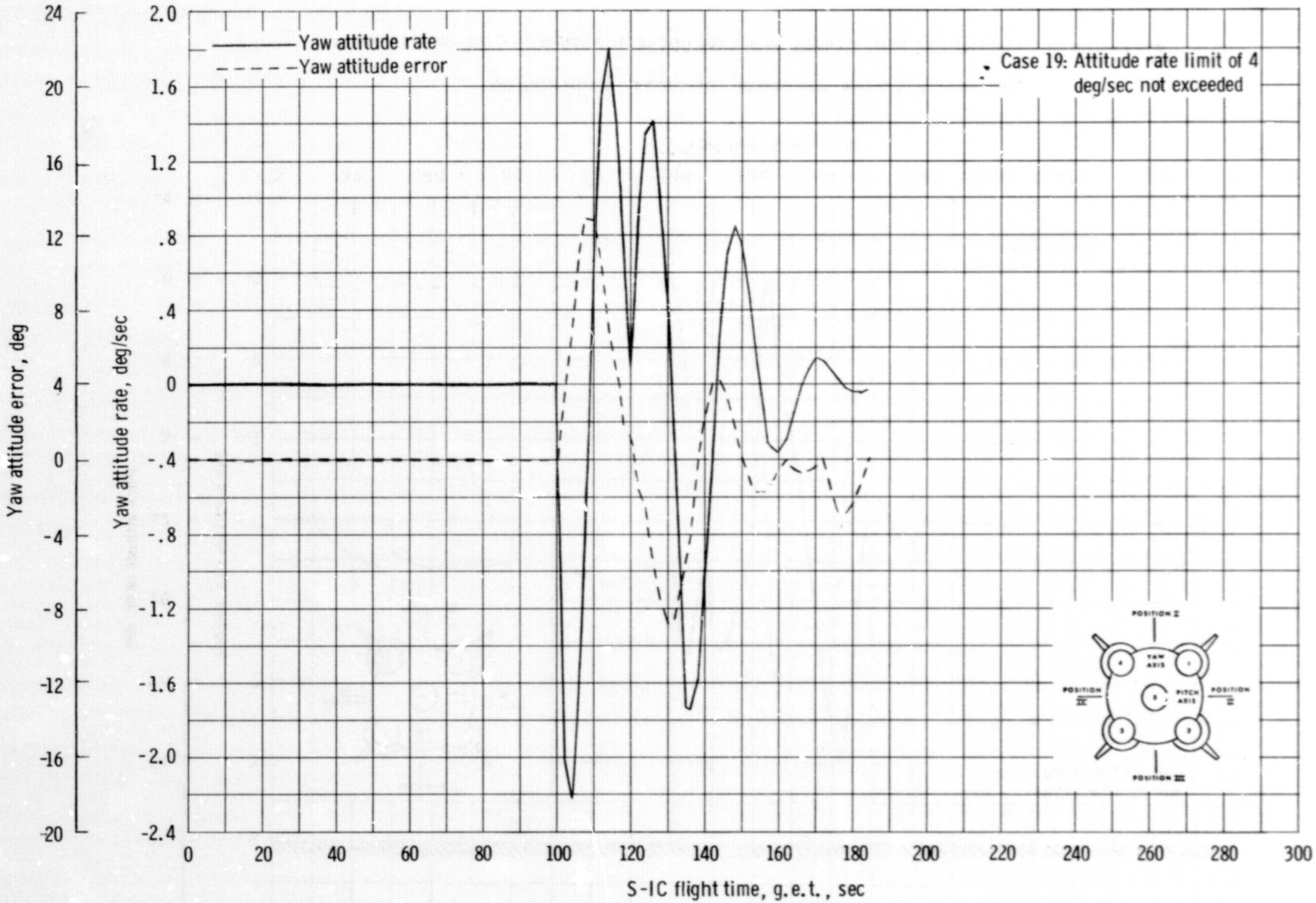
(e) Angle of attack versus altitude.

Figure 7.- Concluded.



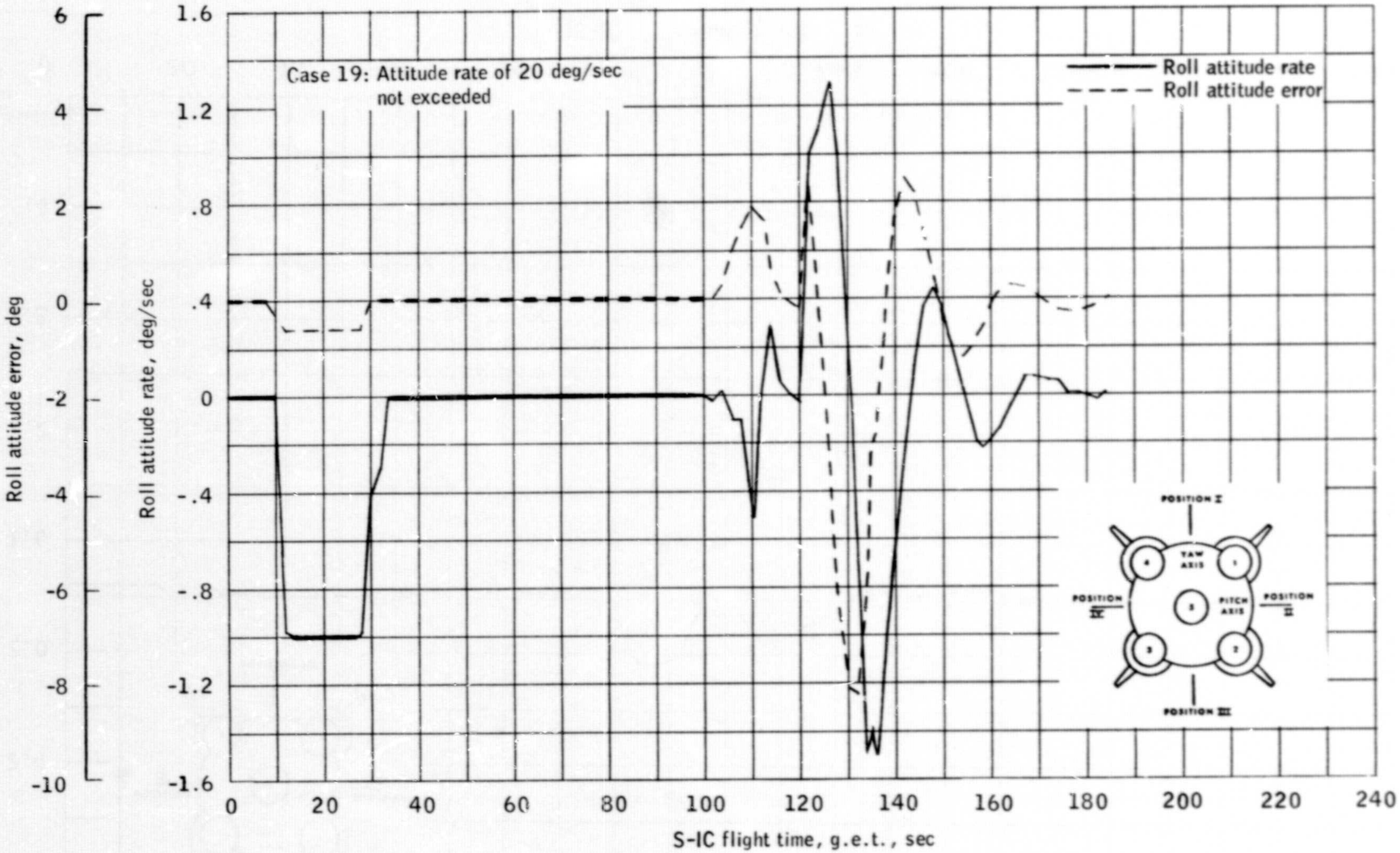
(a) Pitch attitude rate and pitch attitude error versus S-IC flight time.

Figure 8.- Case 19: S-IC engine 2 out at 100 seconds and engine 3 out at 120 seconds ground elapsed time.



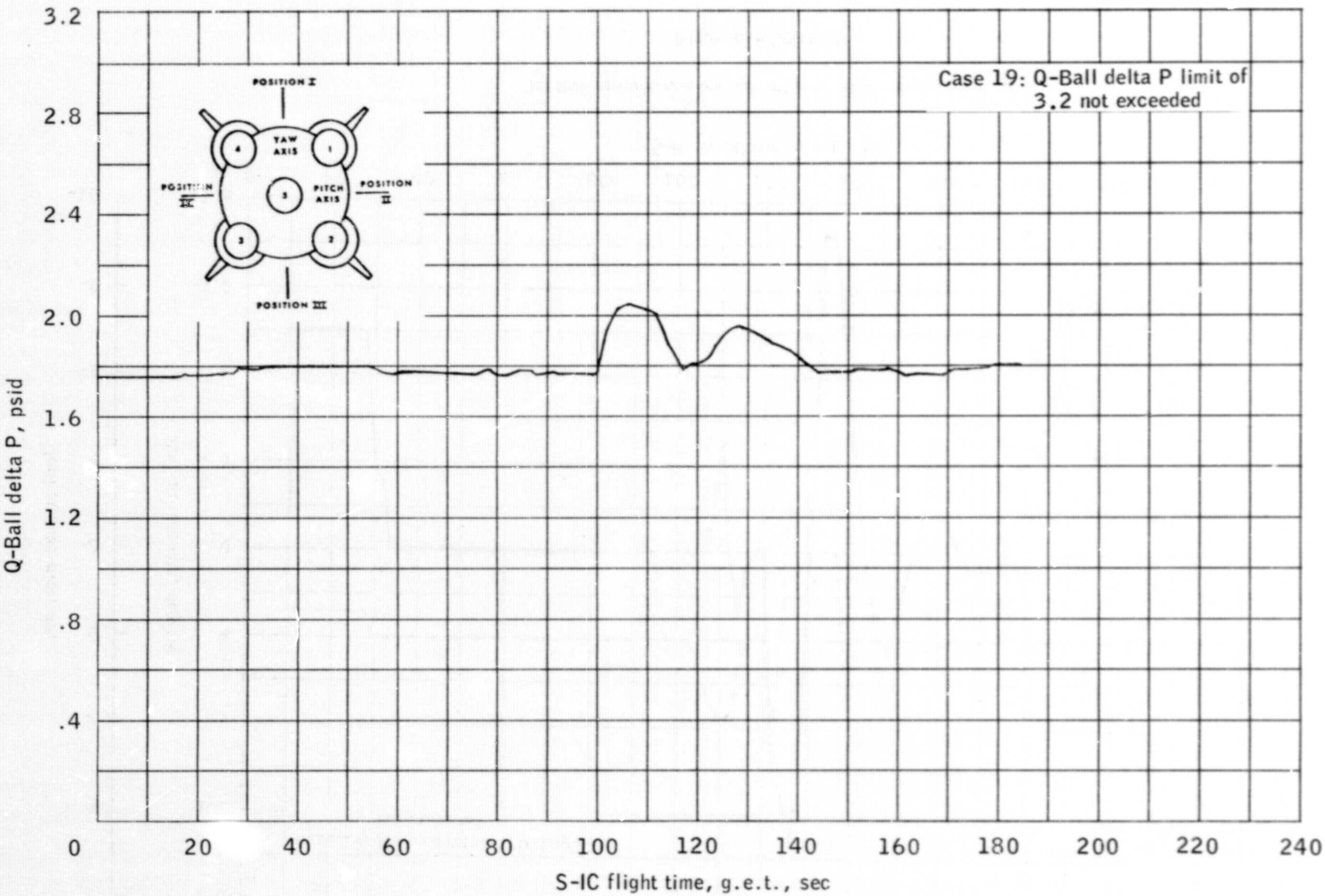
(b) Yaw attitude rate and yaw attitude error versus S-IC flight time.

Figure 8. - Continued.



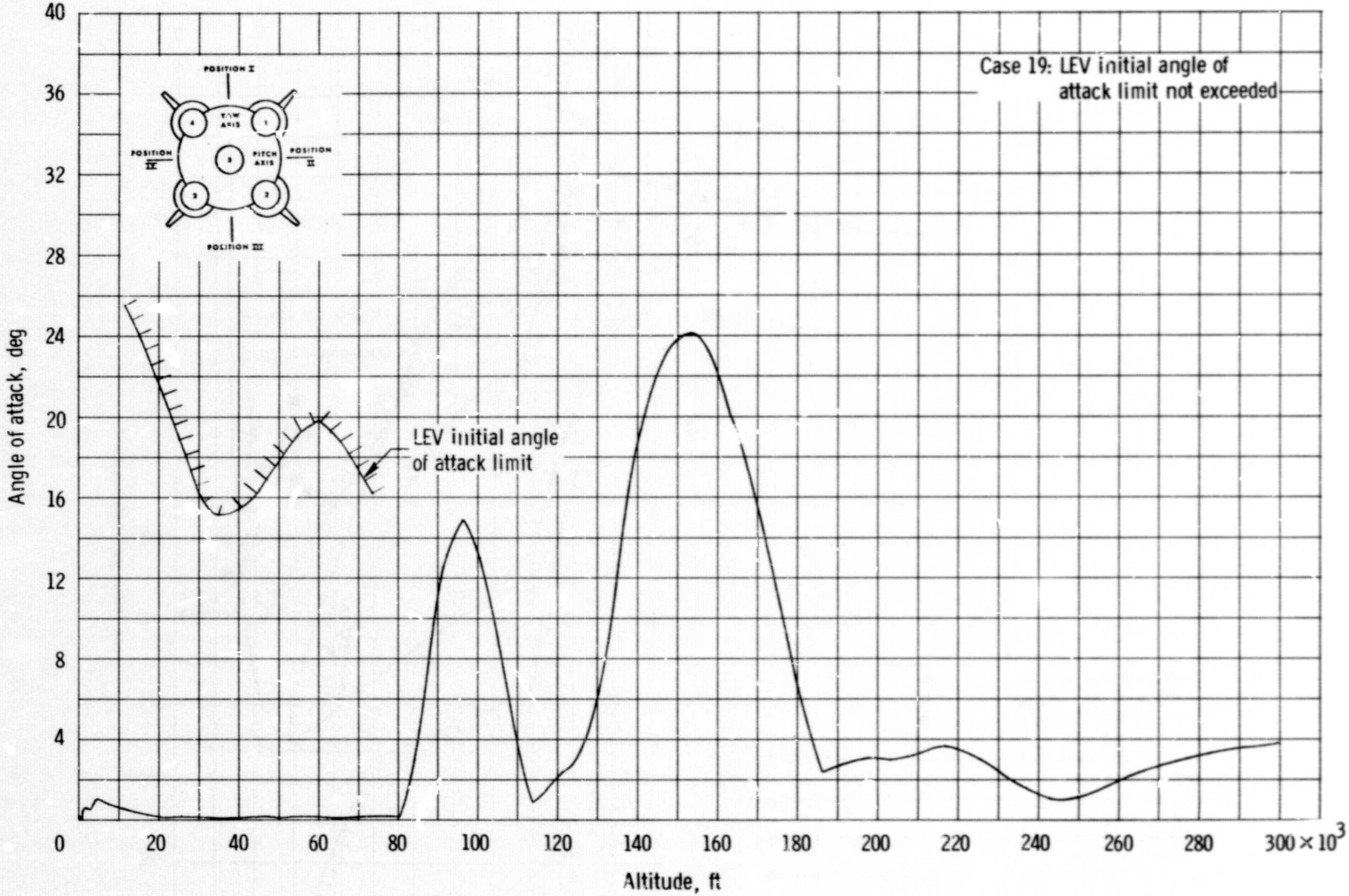
(c) Roll attitude rate and roll attitude error versus flight time.

Figure 8.- Continued.



(d) Q-Ball reading versus S-IC flight t[illegible].

Figure 8.- Continued.



(e) Angle of attack versus S-IC flight time.

Figure 8. - Concluded.

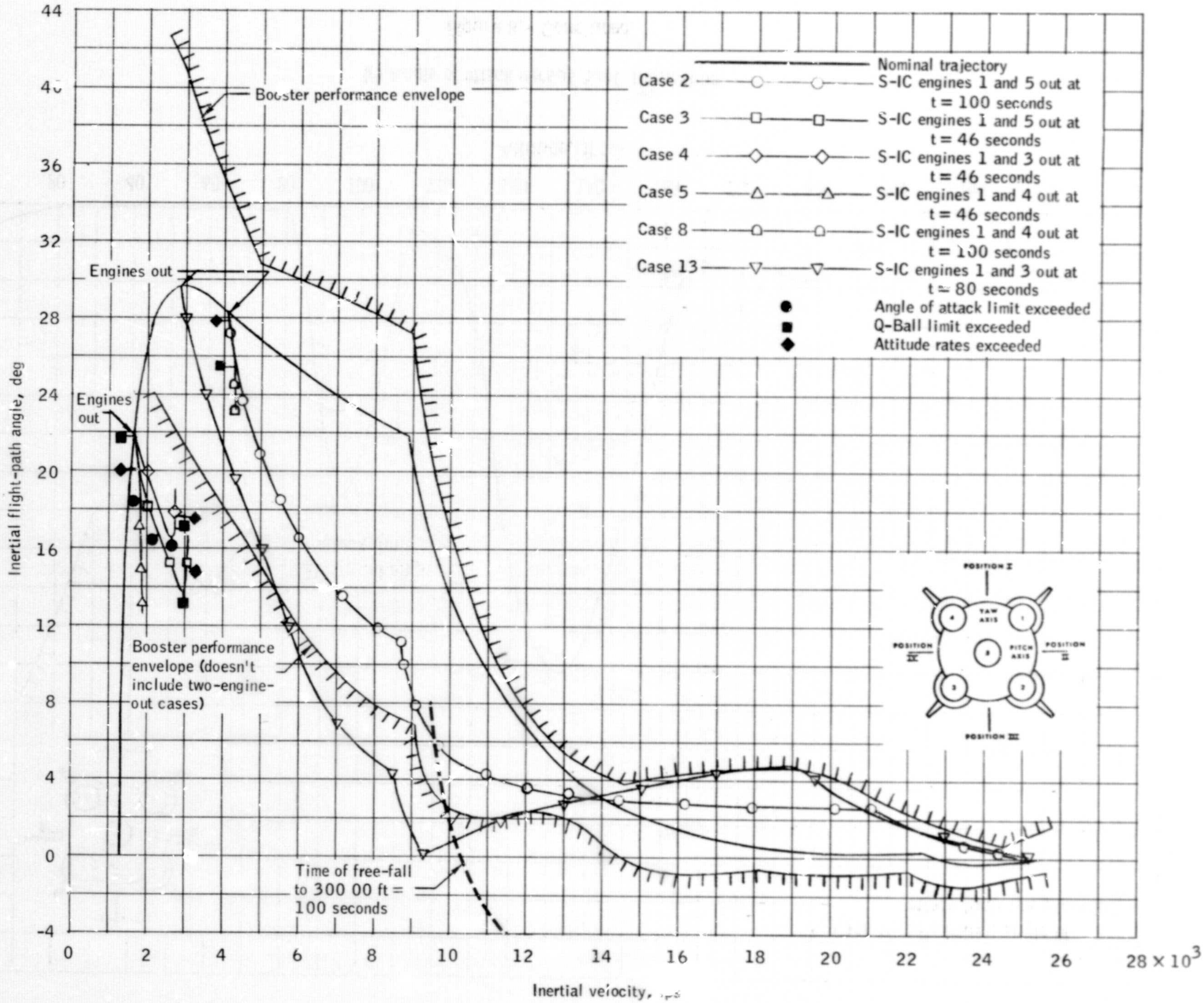


Figure 9.- S-IC two engines out, inertial flight-path angle versus inertial velocity.

REFERENCES

1. Saturn V Two-Engine-Out Study. MSC memo 69-FM36-168, April 21, 1969.